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Antimisting Fuel Research and Development for Commercial Aircraft – Final Summary Report

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16. Abstract

This report covers the research, development, testing, and evaluation conducted by the Federal Aviation Administration (FAA) in pursuit of an effective, feasible antimisting agent for kerosene jet fuels that would prevent or reduce the dangers of postcrash, fuel mist fires. For the past eight years, most of this effort was focused on a high molecular weight polymer, FM-9, as a representative agent to prove the antimisting fuel concept. The results of this work indicate that the goal is achievable: Jet fuel can be modified to provide a significant degree of protection against postcrash fires in impact-survivable accidents. Additional development and testing would be required before the fuel is operationally acceptable. It would be necessary to make some modifications in fuel handling procedures and hardware in aircraft and at airports. But there appear to be no technically insurmountable problems. Keywords!

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PREFACE

Extensive research, development, and testing of antimisting fuels have taken place in the United States and in the United Kingdom for over a decade. Scientists and engineers have learned a great deal about the fuels: their behavior, characterization, flammability, production, and their compatibility with aircraft propulsion systems.

Most of this work has been reported in detail in individual technical reports. This report brings the results of all the antimisting fuel work together for the first time in a systematic manner that summarizes the highlights of the individual reports with comprehensive references for those who wish to learn more about the details.

In essence, this report is a summary of an extensive body of technical literature. Because the technical literature is so extensive, by necessity, the summary itself is also extensive. By the same token, the Executive Summary is longer than normally encountered in a report of this type in order to present all the significant highlights in a meaningful manner.

The reader is also advised to read the captions under each of the illustrations in this report where significant information is presentd about the events pictured.

The author wishes to acknowledge the major contributions made to this report by William T. Westfield, Manager of the FAA Technical Center's Engine/Fuel Safety Branch; Eugene P. Klueg, Antimisting Fuel Program Manager; and Bruce C. Fenton, Assistant Program Manager. The author's task was mainly that of reporting on the research and development work directed by these three people and others who are listed in the reference section.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

EXECUTIVE SUMMARY

Purpose. In 1978, the Federal Aviation Administration (FAA) initiated a program to establish the feasibility of using antimisting additives in jet fuel to suppress postcrash fires in impact-survivable accidents. The additive would have to be effective in preventing the formation of easily ignitable mists when fuel is spilled from ruptured tanks and sheared by onrushing air. The additive should have a relatively low cost and be compatible with aircraft and airport fuel systems. If not added to the fuel prior to being delivered to the fueling point, it would have to be readily blendable and provide fire protection throughout the flight cycle, beginning within 15 minutes of blending.

Background. Evidence from aircraft accident investigations indicates that at least 35 percent of the fatalities in impact-survivable accidents are a direct result of postcrash fires and the accompanying heat, smoke, and toxic gases. An estimated 135 lives on average are lost annually worldwide in impact-survivable accidents because of postcrash fires.

In many impact-survivable accidents, ruptured fuel tanks spill large amounts of jet fuel into the onrushing air stream while the aircraft is still in motion. Sheared by the air, the fuel forms a fine, highly inflammable mist which can be easily ignited by hot engine components, sparks, or other crash-generated ignition sources. Once ignited, the fire rapidly propagates through the mist to the fuel release point and quickly engulfs the aircraft.

In 1978, the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee concluded that antimisting kerosene (AMK) could provide the single, most significant improvement in reducing postcrash fire hazards and recommended expansion of the AMK research then underway by the FAA. In June 1978, the United States and the United Kingdom signed a Memorandum of Understanding (MOU) in which they agreed to pursue a cooperative effort to determine the feasibility of using antimisting additives in civil aviation kerosene jet fuels. The principal participants in this effort were the FAA and England's Royal Aircraft Establishment (RAE), which also had been conducting research in this area. The National Aeronautics and Space Administration (NASA) was designated as a third party to the agreement to perform basic research and provide technical support.

In September 1980, the FAA formulated an Engineering and Development Program Plan on Antimisting Fuel. This plan, revised in February 1983, called for a phased program of research and development to: (a) determine the feasibility of antimisting fuel; (b) develop recommendations for its introduction and use in civil aviation; (c) assess its effectiveness in a controlled impact demonstration; and (d) assess its economic reasonableness in support of regulatory actions. The British antimisting additive, FM-9™, developed by Imperial Chemical Industries (ICI) was selected as the most promising agent then available for the study. This report is concerned with the work performed under FAA's AMK engineering and development program.

The accomplishments under the AMK program during the past eight years are summarized below according to the major elements of the program.

AMK Characterization. FM-9 is a high molecular weight, hydrocarbon polymer. When added to kerosene jet fuel in small amounts — 0.3 percent by weight — it

suppresses the fuel's tendency to form a fine mist when sheared by onrushing air as in an accident. Initially, FM-9 was available only as a powder which had to be batch blended into jet fuel with glycol and amine. It was later produced as a slurry of FM-9 in a glycol-amine carrier fluid which could be inline blended with jet fuel at the fueling point. FM-9 development was frozen during the initial feasibility phase of the program to provide a consistent data base for evaluating the antimisting concept.

Under certain conditions, FM-9 antimisting kerosene behaves as a non-Newtonian fluid with complex rheological characteristics. In order to understand and be able to predict its behavior, FAA and its contractors undertook an extensive rheological study of AMK. Initially, researchers focused on the rheological properties of undegraded AMK that would explain its antimisting behavior. This work eventually led to the conclusion that it was a unique viscosity property generated in AMK as a result of normal stresses that was the rheological characteristic primarily responsible for mist prevention.

A quality control test that would provide a real-time measure of undegraded AMK's antimisting effectiveness was a major goal. The researchers investigated methods for quantifying the viscoelasticity of undegraded AMK based on a die swell technique that measures the expansion of a stream of AMK as it is forced out the end of a capillary tube. They refined this technique to the point where it shows promise as a real-time quality control test.

At the other end of the degradation spectrum, a precise method was needed for characterizing highly degraded AMK that would provide a reliable indication of the fuel's filterability and combustibility. After investigating several analytical techniques, Southwest Research Institute (SwRI) developed a simultaneous filtration/degradation test that appears to be a reliable quality control test for inline blended, highly degraded FM-9 AMK. This test, however, has not been developed to the point where it is suitable for real-time applications.

FAA contractors also made a detailed study of AMK's heat transfer properties to insure that the fuel would perform adequately in the aircraft and engine heat exchangers. While highly degraded AMK and Jet A fuel have nearly the same heat transfer rate, the heat transfer rate for undegraded AMK can be significantly lower. Despite the question of the adequacy of the heat transfer properties of undegraded AMK, no problems were encountered either in engine or flight tests. In all the tests, the heat exchangers were downstream of the degraders. However, no problems were experienced when the degraders were shut down, and the heat exchangers had to work with undegraded AMK fuel.

AMK Flammability. The FAA developed several small- and large-scale test facilities to measure the flammability characteristics of antimisting fuels under simulated takeoff and landing conditions. The large-scale, wing-fuel spillage facility at the FAA Technical Center proved to be the most realistic in simulating the conditions encountered by jet fuels in impact-survivable accidents for which AMK was developed. The small-scale tests were useful in the initial screening of antimisting fuel candidates.

FAA ran over 300 tests on its wing-fuel spillage facility and developed an ignition envelope for AMK as a function of FM-9 concentration, airspeed, fuel spillage rate, ambient air temperature, fuel temperature, and type and location of the ignition source. The results from these tests correlated well with the results of catapult

crash tests of surplus military aircraft conducted by FAA at the Naval Air Engineering Center. The large-scale tests demonstrated that a 0.3 percent concentration of FM-9 in Jet A would prevent the formation of mist-generated fireballs at speeds up to 150 knots and would provide partial protection against fuel mist fireballs at speeds up to 200 knots.

AMK Production. Early in the AMK program, researchers recognized the necessity of blending FM-9 antimisting additives into jet fuels at the aircraft fueling point. Introduction of the additive at an earlier stage would increase costs as well as possibilities of unintentional degradation and contamination. ICI's development of a slurry of FM-9 in a glycol-amine carrier fluid made this possible, but it was still necessary for FAA and its contractors to develop a practical inline blending process.

A 1 liter/minute inline blender was developed incorporating static mixing tubes in a continuous, 3-phase flow system in which the additive is metered into the jet fuel, dispersed, and then dissolved. The final blender that was built and used in the program was a 50-125 gallon/minute unit used in the Controlled Impact Demonstration (CID) test. Larger, commercial size, inline blenders could be manufactured using the same basic components and design.

Early in the program, sodium used in the manufacturing process of FM-9 was detected in AMK at levels that could significantly accelerate hot section corrosion in turbine engines. ICI subsequently supplied FAA with sodium-free samples of FM-9 which were successfully tested on the wing-fuel spillage facility. The company would use the sodium-free process if the demand for FM-9 were to develop.

Studies here and in England demonstrated that AMK developed adequate fire protection properties within 15-20 minutes after being inline blended, provided that the temperature and aromatic content of the base fuel were above, 0° Celsius (C) and 12 percent, respectively. Other studies showed that aromatic content was the only characteristic of different Jet A base fuels that had a significant effect on FM-9 polymer dissolution. For the CID test, FAA developed specifications for FM-9 AMK and its constituents that could be readily adapted to commercial use of the fuel.

Several investigations were conducted here and in England on the effects of water and water vapor on AMK. Bulk water makes the fuel cloudy and can cause a white, sticky precipitate to settle out of AMK. But bulk water can be kept out of aircraft fuel tanks by improved fuel handling procedures. It is possible to control the presence of bulk water in Jet A fuel during the blending process and subsequent fueling of the inline blended AMK into aircraft fuel tanks. The amount of condensed or coalesced water that could get into aircraft fuel tanks under simulated "worst case" flight conditions is too small to cause problems.

AMK Compatibility. The FAA and RAE and their contractors carried out several studies on the compatibility of FM-9 AMK with individual engine components, airframe fuel systems and components, fuel additives, tank sealants and coatings, bladder cell materials, and elastomers.

Of the several approved Jet A fuel additives that were investigated, only the anti-icing agent produced a precipitate in AMK at the maximum allowable concentration. However, because FM-9 AMK has better lubricity than Jet A and contains approximately 1 percent glycol, lubricity and anti-icing additives may not be required. Further studies in this area are warranted.

Engine and fuel system component tests showed that engines could be operated on undegraded AMK but at a loss in efficiency and an increase in carbon monoxide and unburned hydrocarbon emissions. For modern jet engines to operate efficiently on AMK it has to be highly degraded. Researchers investigated several methods for degrading AMK. All resulted in a net energy loss to the engine cycle. Prototype flight degraders were built for use on the B-720 CID aircraft and flight tested on one engine of a CV-880. For expediency, these prototype degraders were developed from an existing military engine centrifugal pump and were oversized for the AMK application. In any future design, the degrader would most likely be made an integral part of the engine fuel pump to minimize weight and energy requirements.

Other compatibility problems, mostly minor, were uncovered in these studies. For example, ejector pumps and probably boost pumps would have to be redesigned to make up for performance losses with AMK. Mesh sizes or filter area of some fine engine filters might have to be increased. Gravity transfer and suction feed performance fell below normally accepted levels at certain conditions. However, it is believed that these deficiencies could be remedied by minor hardware modifications or fuel management procedure changes.

By the same token, researchers encountered problems with soluble and insoluble gels that require more complete explanations. The insoluble gel that occurred in FM-9 AMK during some early flight test and engine test cell work is believed to have been caused by contamination that had accumulated in the system prior to the introduction of the AMK, which is highly detergent. Also requiring further investigation is the gel that forms when regular kerosene fuel is added to a system containing residual AMK or when AMK is added to a system with residual Jet A. Temporary, soft, soluble gels that formed on the downstream side of fine mesh engine fuel filters did not cause operational problems and can be accommodated by increasing the filter size or decreasing the flow velocity.

Before AMK use could be implemented in commercial aviation, long duration service tests and evaluations would be required to answer satisfactorily these questions on proposed changes that will have to be made in current airframe and engine systems to accommodate antimisting fuels safely.

AMK Flight Tests. The primary objectives of the AMK flight test program were to demonstrate the use of FM-9 antimisting kerosene fuel and a prototype degrader on representative transport aircraft and to determine the effects of AMK on the aircraft fuel system performance as well as fuel system effects on the AMK. The two aircraft involved were a Convair 880 in which the No. 3 engine was equipped with a degrader and fueled exclusively with AMK and the Boeing 720 CID aircraft in which all four engines were equipped with degraders and fueled with AMK.

The flight test program was successful. Except for the insoluble gel that formed on the CV-880 filters early in the program, the AMK and degraders performed satisfactorily. There were no major degrader system hardware failures or design problems. Ground starts, altitude relights, engine acceleration/deceleration performance were all on a par with Jet A performance. The AMK maintained its mist suppression qualities throughout the flight test environment.

Controlled Impact Demonstration (CID). The B-720 aircraft (operating solely on AMK), on its final flight, was to be remotely flown into the California desert for a carefully planned survivable impact that would demonstrate AMK's fire protection potential. The final flight deviated from the planned flight profile and exceeded the design goals for AMK fuel.

Because of the high yaw angle of the aircraft at impact with steel wing openers embedded in the desert site, a major ignition source occurred at the fuel release point. Initial ignition occurred when a wing opener failed the right inboard engine. This initial fire appeared to involve lubricating oil, hydraulic fluid, and degraded AMK. It engulfed the fuselage but went out after eight seconds leaving the aircraft with relatively little fire damage. However, burning fuel entered openings sliced into the lower fuselage by the wing openers and eventually destroyed the aircraft.

While no experiment as complex as the CID can be expected to go exactly as planned, a careful review of 20 years of accident data indicated that CID was a unique accident. The data on the 700 accidents examined revealed no impact-survivable accident that had all the critical elements of CID. The conclusion: If CID had occurred as planned, in all probability the antimisting characteristics of AMK would have prevented the postcrash fire.

Post-CID Studies. Following the impact demonstration, FAA undertook studies to determine exactly what happened and why. It conducted a series of experiments at the Technical Center that were designed to duplicate the critical parameters of CID such as high yaw angles and recirculation areas of high shear in order to determine their effects on spilled fuel under controlled conditions.

In essence, these studies along with researchers intensive examination of the detailed photographic data on CID confirmed that the FM-9 AMK fuel had been subjected to conditions well beyond those for which it was designed to provide post-crash fire protection and, based on past accident data, conditions considered extremely unlikely to occur in impact-survivable accidents.

The tests also turned up a potentially serious problem not relevant to the CID, but one that will require additional research in any future work on antimisting fuels. If AMK becomes entrained in the engine exhaust where it is exposed to severe shear forces, an extremely fine mist can result which can be readily ignited if a flame source is present.

Cost Considerations. Due to the present high level of air travel safety, the use of FM-9 antimisting fuel is difficult to justify solely on an economic basis. Economic studies for the FAA showed a low benefit-to-cost ratio. However, they also calculated that the use of FM-9 would require only a 2 to 3 percent increase in the price of an airline ticket. This would cover the cost of the AMK as well as the costs for any required aircraft and airport fuel system modifications.

CONCLUSIONS

The results of eight years of development and testing indicate that antimisting kerosene fuel would provide a very high degree of protection against postcrash fuel mist fires in impact survivable accidents. Some additional research would be required along with long duration service tests and evaluation. The use of safety fuels, particularly as part of an overall systems approach, merits serious consideration in future aviation safety technology development programs.

INTRODUCTION

Detailed studies of impact-survivable aircraft accidents indicate that approximately 135 lives worldwide and 21 domestically, on the average, are lost annually because of post-crash fires (references 1, 66, and 73).

In June 1978, the Federal Aviation Administration (FAA) and the Royal Aircraft Establishment (RAE) signed a Memorandum of Understanding (MOU) (appendix A) in which the United States and the United Kingdom agreed to "cooperate in the examination, development, and testing of antimisting kerosene (AMK) fuels and of equipment related to the use of such fuels" that would provide flammability protection to jet aircraft in impact-survivable accidents. The National Aeronautics and Space Administration (NASA), a third party to the MOU, agreed to perform basic research and provide technological support.

That same year, the FAA established the Special Aviation Fire and Explosion Reduction (SAFER) committee to evaluate all programs designed to increase the probability of survival in accidents involving fire. The SAFER committee concluded that AMK fuels could provide the single most significant safety improvement for reducing the postcrash fire hazard and recommended continuing and expanding AMK research because of the substantial reductions in fatalities it could provide (reference 2).

Consequently, in conjunction with the MOU, the FAA developed a phased, 6-year development and evaluation program with the following goals (reference 3):

- o Establish the feasibility of using antimisting kerosene fuel.
- o Develop recommendations for the introduction and use of AMK.
- o Demonstrate the effectiveness of AMK in an impact-survivable accident.
- o Assess the economic reasonableness of using the fuel in support of regulatory action.

The FAA and RAE selected FM-9™ (registered trademark of ICI), an antimisting additive which had been under development since the early 1970s, as the most promising candidate for this study. Developed by Imperial Chemical Industries (ICI) and its wholly owned subsidiary, ICI Americas, FM-9 is a high molecular weight, hydrocarbon terpolymer. At FAA's request, FM-9 formulation changes were prohibited during the feasibility phase to provide a common data base that could be used in evaluating the antimisting concept.

Initially, ICI supplied FAA and its contractors with jet fuel in which the FM-9 powder had been batch blended in three steps. Later, ICI developed a glycol-amine carrier fluid for the FM-9 which enabled the additive to be inline blended with jet fuel at the point of use. This significantly reduced logistics problems and minimized unintentional degradation. Also, it would have been unfeasible, if not impossible, for the airlines to use FM-9 in powdered form due to operational constraints. For their initial studies, however, it was necessary for the FAA and its contractors to use batch-blended AMK until 1983, when it became possible to make inline-blended fuel with the FM-9 slurry.

The resultant antimisting kerosene fuel, Jet A with a 0.3 percent by weight concentration of FM-9, demonstrated impressive, fire resistance properties in numerous small- and large-scale tests, both here and in England. When AMK is sheared by onrushing air (as it would be when spilling from ruptured fuel tanks in an aircraft accident), it thickens, forming large, difficult to ignite droplets instead of the fine, readily ignitable, jet fuel mists usually generated in crashes (figure 1).

After two years of intensive investigations with the FM-9 additive, researchers concluded in November 1980 that (1) AMK was feasible; (2) it offered benefits in the form of greatly increased resistance to postcrash fuel mist fires; and (3) there were no technically unsolvable problems that would preclude its operational use. Federal Aviation Administration (FAA) and NASA then initiated research efforts that would lead to full-scale ground and flight tests, culminating in a transport aircraft crash demonstration in 1984.

Before beginning the program, the FAA recognized that AMK was a high risk program that might not work and would not be cost beneficial in the classical sense. But if successful, the payoff in lives saved would be high.

Under Phase 1 of its engineering development program on AMK (reference 3), the FAA set out to establish the basic characteristics of AMK, namely: flammability, rheology, degradability, blending, handling, specifications, performance, and compatibility. Phase 1 also called for large-scale evaluation and economic studies of AMK. (As used in this report, AMK refers to FM-9 antimisting fuel, unless otherwise specified.)

DISCUSSION AND RESULTS

AMK CHARACTERIZATION.

Under certain conditions, antimisting kerosene behaves as a non-Newtonian fluid with complex rheological characteristics. In order to understand and be able to predict its behavior and characteristics, it was necessary for the FAA to undertake an extensive rheological study of AMK in its degraded and undegraded state over a broad range of temperature and flow conditions. It was also necessary to study its behavior as a function of the formulation and blending procedures used in its preparation.

In addition to its own work on AMK characterization at the Technical Center, the FAA sponsored research at Southwest Research Institute (SwRI), NASA's Jet Propulsion Laboratory (JPL), and at United Technologies Corporation's Pratt & Whitney Aircraft Group (PWA). Initial research efforts were focused on determining the rheological characteristics of undegraded AMK that were responsible for its antimisting behavior. This early work was carried out with batch-blended fuel.

Early rheological experiments at JPL and SwRI with capillary tube viscometers showed that the shear viscosity of AMK increases suddenly when a critical shear rate ($1000\ s^{-1}$ to $3000\ s^{-1}$) is exceeded (references 4 and 5). But this increase in shear viscosity, even at shear rates well above the critical value, is not large enough to account for AMK's ability to resist atomization at airspeeds of 150 knots and higher.

It now appears that the large extensional viscosities (viscoelasticity) generated in AMK as a result of normal stresses are the dominant rheological characteristic

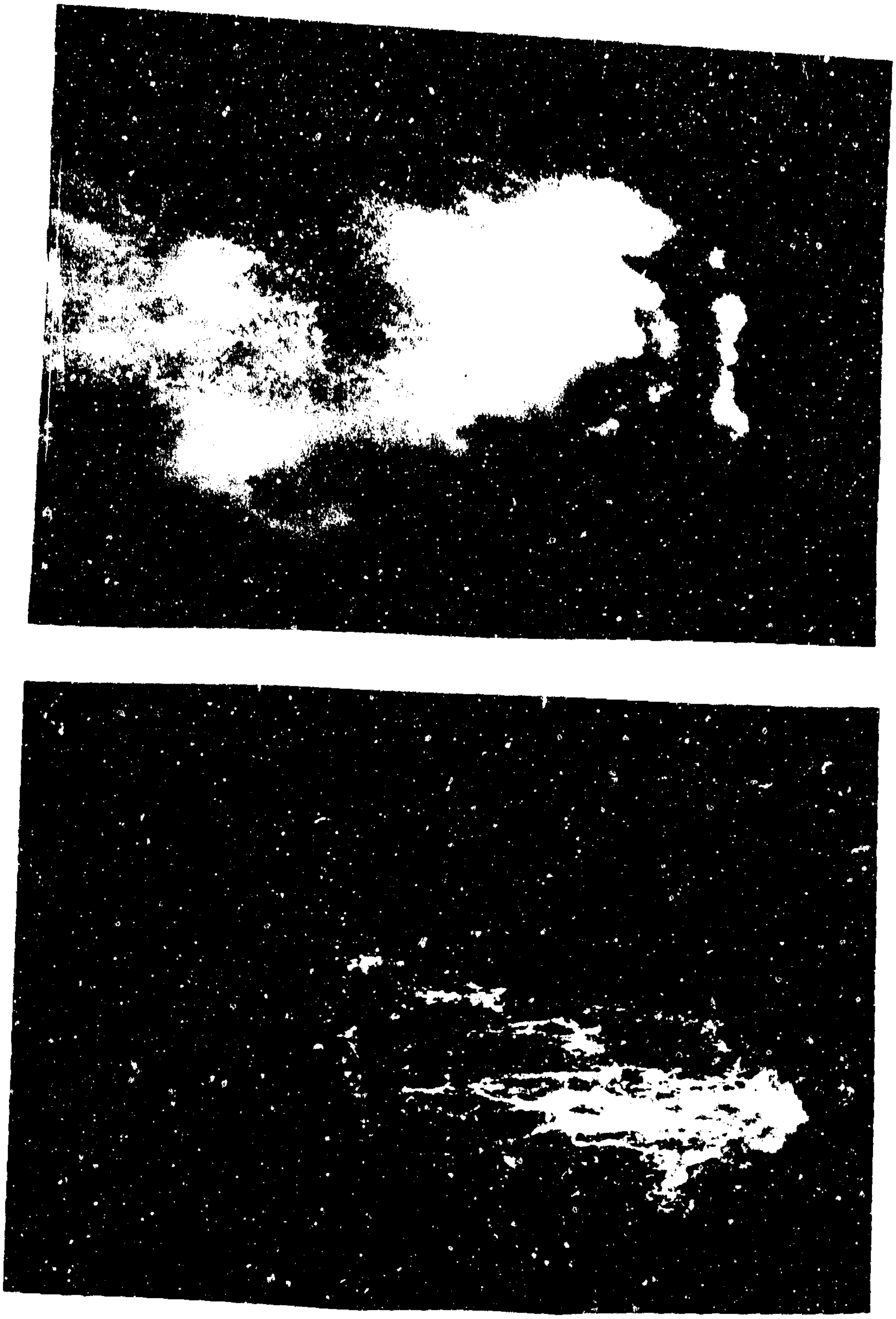

FIGURE 1. BREAKUP OF JET A AND AMK BY HIGH VELOCITY AIR
High velocity air breaks up stream of Jet A into fine mist (top) but produces only a sheeting action on AMK stream (bottom) which hangs together as ligaments and large droplets in tests at JPL.

responsible for its mist prevention behavior. Studies have shown that the normal stresses generated in AMK flows are much higher than the shear stresses. In experiments at SwRI, FM-9 AMK was forced through capillary tubes at high shear rates and over long shear times. As it was forced out the tip of the capillary tube, the AMK jet swelled noticeably indicating its high viscoelasticity (reference 6).

The FAA and SwRI developed methods to quantify the viscoelasticity of undegraded AMK for use as a real-time quality control test of antimisting effectiveness (references 7 and 10). This test is based on the die swell technique that measures the expansion of the jet of AMK as it is forced out the end of the capillary tube (figure 2).

Center engineers were able to estimate the effective concentration of AMK additive during the inline blending process using die swell data taken over a fixed range of shear rates at discrete time intervals (reference 7). The sensitivity of the concentration estimates for a given batch of slurry was determined to be within 0.02 of the nominal 0.30 percent. Moreover, the predicted concentration correlated well with the fuel's fire protection performance on the FAA's wing-fuel spillage facility (figure 3). Based on normal stress properties, the die swell appears to be a practical, real time, quality control test for AMK.

Due to its relationship to normal stresses, the die swell test should have a better theoretical and physical relationship to AMK's antimisting behavior than an orifice flow cup test, which had been the primary quality control test recommended by ICI for undegraded AMK (reference 8). Experiments at SwRI showed that the orifice flow cup is essentially a viscometer that measures the shear viscosity of AMK above its critical shear rate and, alone, is not a reliable indicator of the fuel's antimisting performance.

The FAA and its contractors also worked on the development of more precise methods for characterizing highly degraded (low misting resistance) FM-9 AMK. The degradation level of AMK is a reliable indicator of the fuel's filterability and combustibility. The standard procedure for quantifying the level of degradation initially was a filter ratio test (reference 9). This test is a ratio of the time required for a known quantity of AMK to flow through a nominal 17 micron, Dutch weave, stainless steel filter to the time it takes for the same quantity of Jet A to flow through. A value close to 1 indicates a highly degraded fuel with flow properties similar to Jet A; 40 or above indicates a highly undegraded fuel. But the filter ratio test lacks the sensitivity needed for reliable indications of the filterability of very highly degraded AMK (FR $\leq$ 1.2). Consequently, FAA and its contractors began investigating other methods for evaluating the properties of highly degraded AMK.

Southwest Research Institue developed a small-scale, pump filtration test that simulated filtration conditions in an aircraft fuel system to measure the filter plugging characteristics of intentionally degraded AMK (reference 6). In this test, degraded AMK is forced through a small section of a paper filter or metal screen using a variable speed gear pump. The pressure drop across the filter, due to flow resistance, is measured as a function of flow time and superficial velocity (flow rate/filter area). Below a critical flow velocity (CFV), the pressure drop across the filter remains constant. When the superficial velocity of the flow through the filter exceeds the CFV for that filter, there is a sharp rise in the pressure differential across the filter. This increase in the pressure differential results from an increase in viscosity and, possibly, from the formation of a

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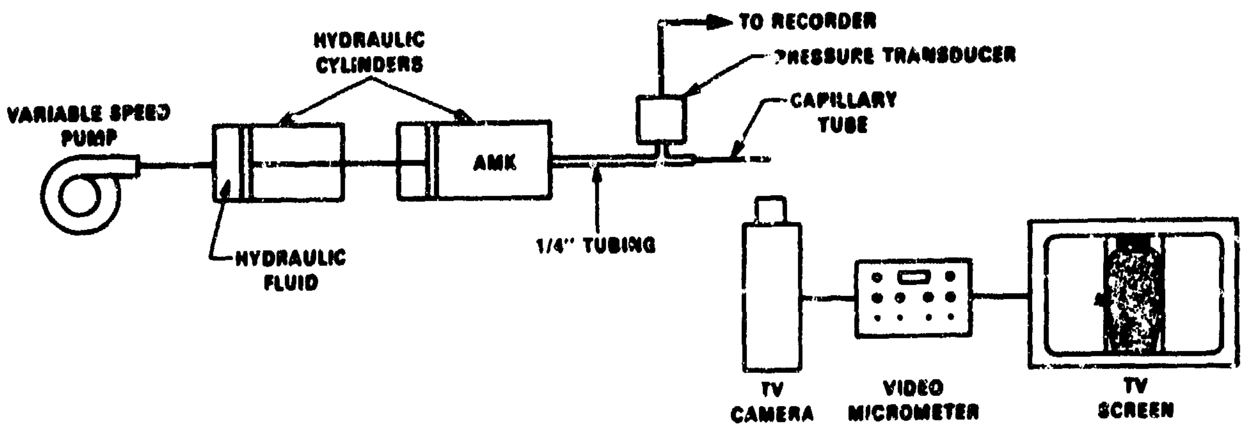

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FIGURE 2. PICTURE AND SCHEMATIC OF DIE SWELL RHEOMETER
FAA engineer (top) uses die swell rheometer to measure shear viscosity and die swell of AMK samples at high shear rates. Schematic of die swell apparatus is shown (bottom).

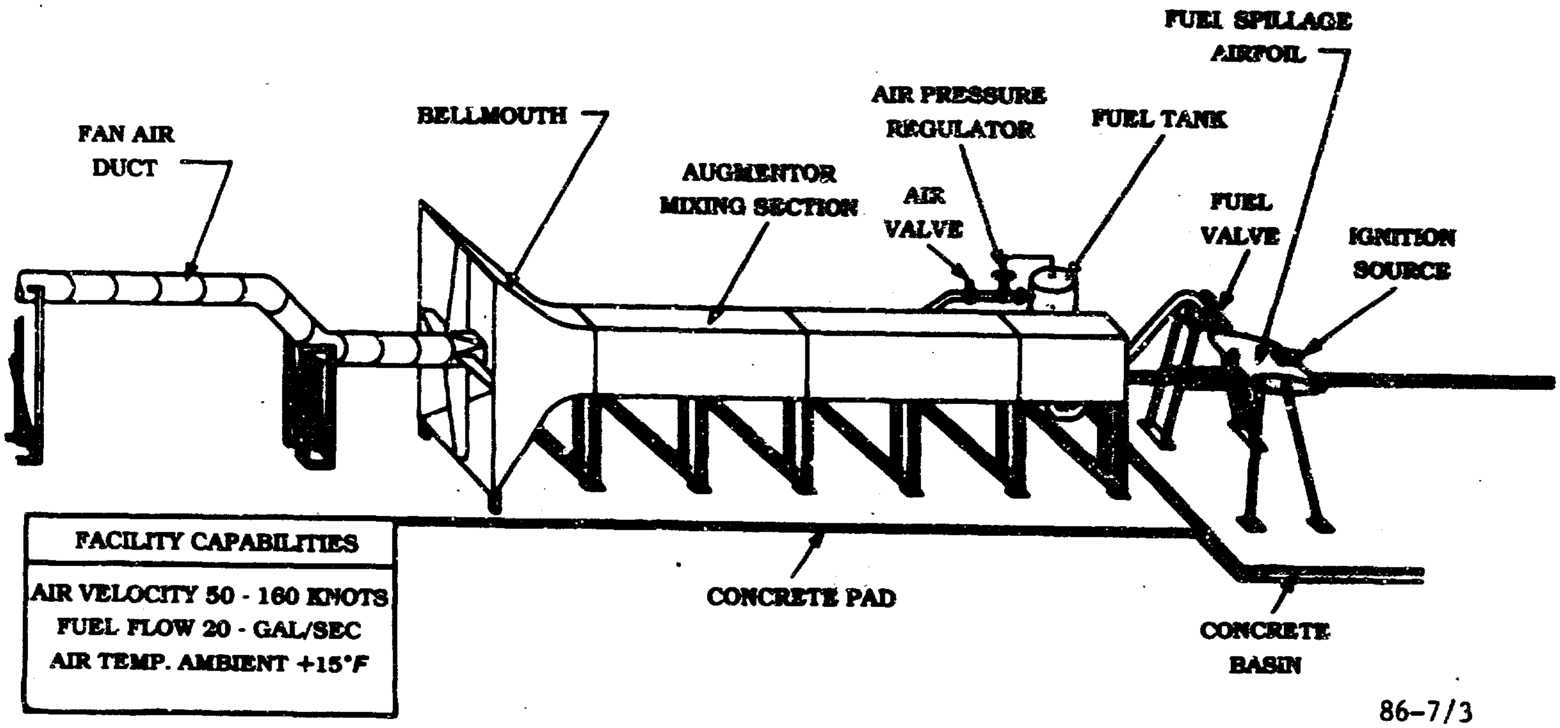


FIGURE 3. WING-FUEL SPILLAGE FACILITY
FAA Technical Center ran over 300 tests of different antimisting fuels on its large scale, wing-fuel spillage facility to measure fire protection performance.

transient, shear-induced gel on the downstream side of the filter. For batch-blended AMK, the pump filtration test can be used to predict the filter plugging characteristics of highly degraded AMK. For inline blended AMK, however, the pump filtration test requires an equilibration period that would preclude its use as a real-time quality control test.

A simultaneous filtration/degradation test developed by SwRI, shows promise as a real-time quality control measure for inline-blended, highly degraded AMK (references 10 and 11). In special apparatus developed by SwRI, inline blended AMK is forced through a needle valve under high pressure (1000 to 5000 psi) and immediately flows through a small section of metal screen or paper filter. The pressure drop across the filter is then measured as a function of time to determine the critical velocity for the filter. Using this test, SwRI found that freshly blended AMK is only slightly more resistant to degradation than fully equilibrated AMK and develops satisfactory mist fire protection within 30 minutes of blending. This prototype test, however, has not been developed to the point where it is suitable for real-time applications.

Working under a NASA contract, PWA developed the transition velocity test, which is used in conjunction with gel permeation chromatography (GPC) to predict the filterability of highly degraded, batch-blended AMK (reference 12). Transition velocity is a more sensitive test than filter ratio. The average velocity of AMK flowing through an 18 micron filter is plotted against the vacuum applied downstream of the filter. The point at which the slope of the plot changes is defined as the transition velocity. However, transition velocity is not expected to be a reliable indicator of filterability for inline blended AMK. Nor is it suitable for real-time use.

The FAA and SwRI also evaluated gel permeation chromatography as a characterization test for highly degraded AMK (references 13, 14, and 15). It was able to discriminate among different samples of highly degraded AMK. But it was not able to predict the filterability of even highly degraded AMK — due to the presence of small amounts of undegraded or partially degraded FM-9 polymer — as well as the pump filtration test could. Moreover, because of the time required to run the test, GPC is not suitable as a real-time quality control test for inline blended AMK.

HEAT TRANSFER PROPERTIES.

The FAA contractors also made a detailed study of the heat transfer properties of AMK to insure that aircraft and engine heat exchangers would perform satisfactorily with the FM-9 antimisting fuel.

In its study, PWA determined the heat transfer coefficient of batch-blended AMK by flowing it through a single pass, single concentric aluminum tube heat exchanger similar to the type used in its JT8D turbofan engine (references 12 and 13). To degrade the fuel, PWA passed it through the JT8D fuel pump one or more times. PWA results showed that at low flow rates, the heat transfer coefficients of degraded AMK and Jet A were almost identical (figure 4). At higher flow rates (150 kg/hour), the degraded AMK heat transfer coefficient was about 10 percent lower than that of Jet A but still considered marginally acceptable for use in engine heat exchangers. PWA considered the heat transfer characteristics of undegraded AMK unacceptable. The FAA, however, encountered no problems with the heat transfer characteristics of degraded or undegraded AMK during flight tests and engine test cell work.

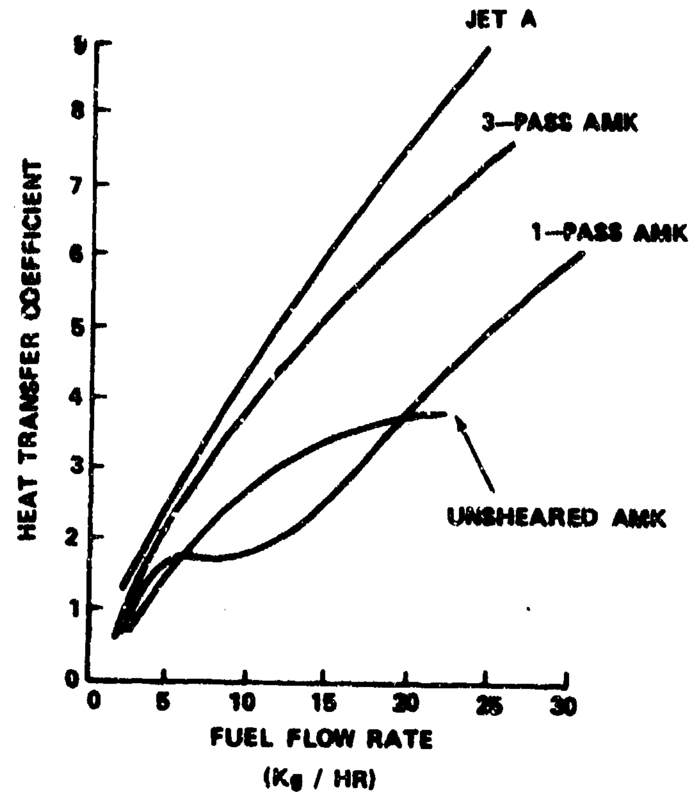


FIGURE 4. AMK HEAT TRANSFER GRAPH
Heat transfer properties of highly degraded (3-pass) AMK closely approximated those of Jet A in tests at Pratt & Whitney

JPL undertook generalized flow and heat transfer experiments to define the flow behavior of FM-9 AMK (reference 16). The JPL work was also done with batch-blended fuels at different levels of degradation. In addition, JPL used different concentrations of the FM-9 additive and measured heat transfer characteristics over a range of fuel temperatures from 20° Celsius (C) to 40° C. JPL also did flow visualization studies to determine whether the flows were laminar, transitional or turbulent.

Researchers at JPL concluded that the flow and heat transfer behavior of AMK can be divided into three regions: Newtonian laminar region, shear-thickening region, and drag reducing turbulent region. At low flow rates, AMK behaves as a Newtonian fluid with constant viscosity at a given temperature and has a heat transfer coefficient equivalent to Jet A. At a certain, critical, wall shear rate, which depends on the fuel temperature and additive concentration, shear thickening occurs and causes a large increase in skin friction and heat transfer rates. The shear thickening and increase in skin friction and heat transfer rates were not observed in low polymer concentrations (0.1 percent) or in partially degraded AMK. In the drag reducing turbulent region, skin friction and heat transfer rates dropped rapidly, falling below the predicted Newtonian values and resulting in a lower heat transfer capability than Jet A.

AMK FLAMMABILITY.

Rheology also plays a dominant role in the antimisting performance of AMK. The major effect of the antimisting additive on jet fuel flammability is rheological rather then chemical. The additive inhibits the fuel's tendency to form a fine, readily ignitable mist under shear and promotes the formation of large droplets which are more difficult to vaporize and ignite.

The FAA has developed a variety of test facilities to measure the flammability characteristics of antimisting fuels under various simulated takeoff and landing crash conditions. These include the FAA's large-scale, wing-fuel spillage test facility and the small-scale, Flammability Comparison Test Apparatus (FCTA), JPL's miniwing spillage test unit and its spray characterization/image enhancement system, SwRI's spinning disk test, and the Naval Air Engineering Center's (NAEC) large-scale, aircraft crash test catapults.

While all of these flammability test units provide meaningful information, the FAA's large-scale, wing-fuel spillage test facility is the most realistic in simulating the conditions encountered by jet fuel in impact-survivable accidents (reference 17) with the exception of the NAEC catapult tests. This facility uses the fan discharge air from a stationary turbofan engine to drive an augmentor. The high volume, high speed airflow from the augmentor flows over a wing section at speeds up to 200 knots. Nominally, 85 gallons of AMK from a pressurized tank are piped at 20 gallons/second into the wing section and out through an orifice in its leading edge. The discharge from the augmentor blows the fuel back over and under the airfoil. A propane torch underneath the airfoil serves as the ignition source. High speed cameras record ignition and flame propagation characteristics.

The FAA researchers ran more than 300 tests on the wing-fuel spillage rig and developed an ignition envelope for AMK as a function of FM-9 concentration, airspeed, fuel spillage rate, ambient air temperature, fuel temperature, and location, type and intensity of the ignition source (references 17 and 18). The results from these tests, conducted with both inline- and batch-blended AMK, showed that a 0.3 percent concentration of FM-9 in Jet A will prevent the growth of mist-generated fireballs at speeds up to 150 knots.

Fuel ignition existed only as localized flame intensification at the ignition source with small, self-extinguishing fireballs aft of the airfoil. There was no mist flashback or flame propagation. Even at simulated airspeeds above 150 knots, AMK fireballs — unlike those of Jet A — propagated relatively slowly, and the flames did not propagate upstream to the simulated tank rupture. These results indicated that a 0.3 percent concentration of FM-9 in Jet A would protect an aircraft from fuel mist fires at impact speeds up to 150 knots and provide partial protection at speeds up to 200 knots.

To validate the results from the wing-fuel spillage tests, the FAA conducted a series of large-scale, catapult crash tests with surplus military aircraft at the Naval Air Engineering Center (references 19, 20, and 21). In these tests, the aircraft fueled with AMK or Jet A were accelerated along a 7,500-foot track by a jet pusher car and impacted into a prepared crash site (figure 5). Ignition sources were placed in the impact area and on the test aircraft. The results from the catapult crash tests and the wing-fuel spillage tests showed good correlation, reinforcing confidence in the wing-fuel spillage test as a valid indicator of AMK's effectiveness.

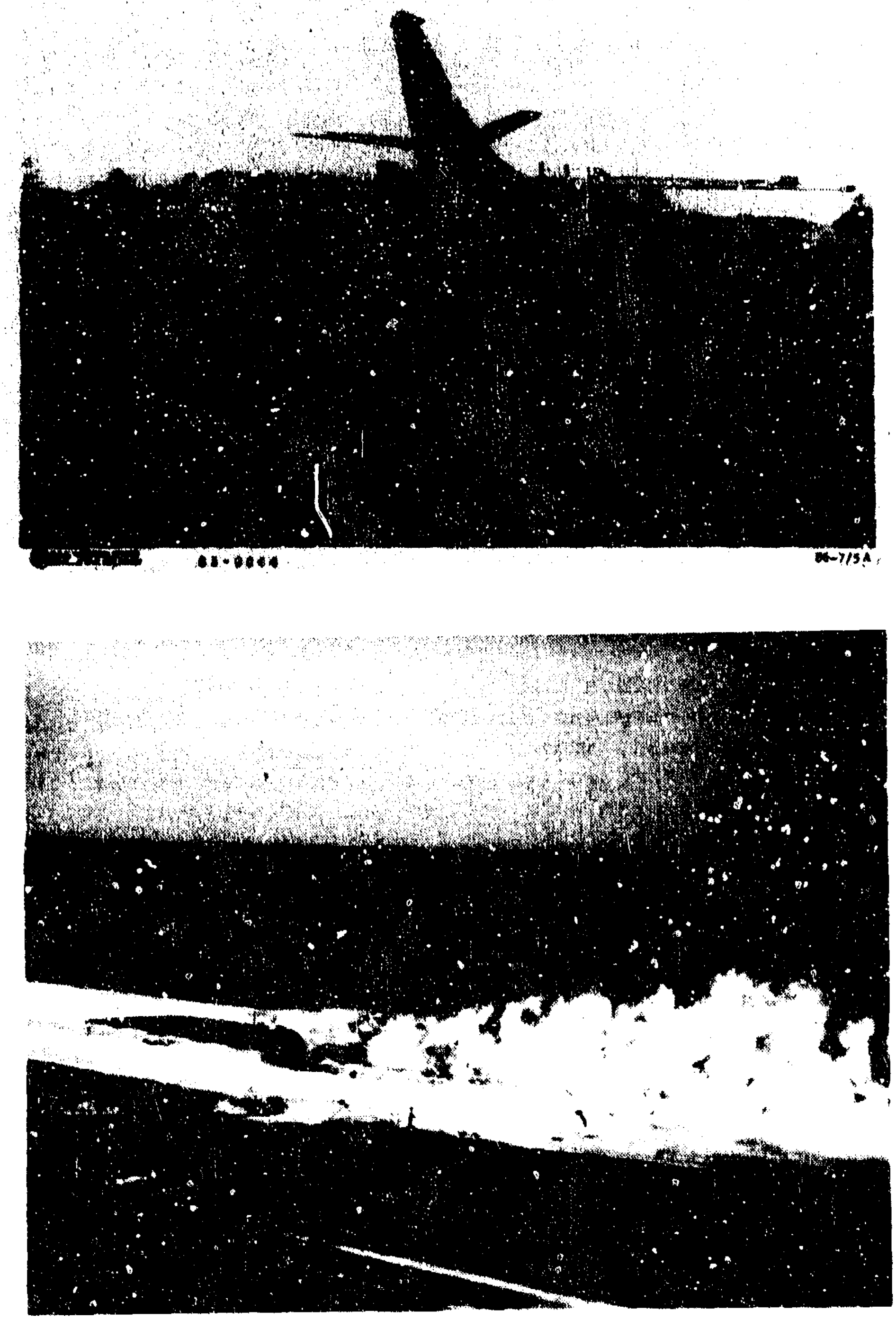


FIGURE 5. CATAPULT CRASH TEST
Results of catapult crash tests of AMK in obsolete military aircraft correlated well with wing-fuel spillage test results. When fire occurred, it didn't propagate forward to fuel release point.

Under an FAA contract, Falcon Research & Development Company attempted to establish correlations among the results of the different flammability tests (reference 22). Falcon found that large- and full-scale crash simulations provided creditable data for an antimisting fuel. Small-scale flammability tests were generally effective for screening antimisting fuels and yielded repeatable data. But the results from different small-scale tests didn't correlate well with each other nor with the results from large-scale flammability tests. Nevertheless, the small-scale tests were useful to researchers for evaluating specific characteristics of antimisting fuels (reference 8).

Results of tests on JPL's miniwing shear apparatus correlated with large-scale test results from the wing-fuel spillage rig and catapult test tracks, according to JPL researchers. Designed to generate controlled fuel sprays, the miniwing shear apparatus provided a steady-state simulation of a fuel spill during an airplane crash (reference 9). As in FAA's wing-fuel spillage facility, fuel was ejected from the leading edge of an airfoil and blown back over the airfoil by a free-jet wind tunnel. An oxyacetylene torch served as the ignition source.

The JPL researchers used the miniwing shear apparatus to study mist formation and flammability of FM-9 AMK at different levels of degradation and over a range of simulated airspeeds from 40 to 160 knots. Initially, the correlation of test results from the miniwing facility with those from the wing-fuel spillage rig was poor. Subsequently, JPL modified its miniwing shear apparatus by increasing the intensity of the ignition source, thereby improving the correlation of test results with those from the FAA's wing-fuel spillage facility.

They conducted several tests to determine the conditions under which a stable, self-supporting flame could be established near the fuel release point following exposure to a transient ignition source. Using flame anchoring as an absolute pass-fail criterion, JPL researchers conducted tests with Jet A, undegraded AMK, and different levels of degraded AMK. They varied airspeed, fuel flow rates and the intensity of the ignition sources (an electrical spark and an oxyacetylene torch).

Results of the JPL tests confirmed that AMK flammability increased with the level of degradation. For Jet A, an electrical spark of 0.067 kw was sufficient to ignite the fuel and produce a self-supporting flame at airspeeds as low as 39 knots. But AMK containing 0.3 percent FM-9 couldn't be ignited by an electrical spark. Even with an oxyacetylene torch of 90 kw, JPL couldn't achieve ignition at simulated airspeeds up to 156 knots and fuel flow rates up to 10 gal/min. When AMK ignition was achieved, the flame was not self-supporting once the ignition source was turned off (reference 9).

These tests showed that if the ignition source was intense enough, all fuels would ignite. Over the range of conditions used in the JPL tests, fuel misting properties and aerodynamics determined whether or not the flame was self-supporting, once ignition was achieved. Self-sustaining flame anchoring in the wake of a bluff body depended on free stream airspeed and the fuel's rheological properties and was independent of the initial ignition source intensity. It should be noted that JPL was unable to ignite 0.3 percent FM-9 AMK at speeds up to 155 knots during the cylinder flame anchoring tests even at the highest acetylene flow rate in the ignition torch. They then decided to use degraded AMK in the tests to determine the pass-fail boundary as a function of airspeed and the degree of degradation.

In its fuel spray characterization work, JPL used the miniwing shear facility to generate controllable fuel sprays for computer enhanced, photographic analysis. The spray characterization was based on digital analysis of high resolution, wide field spray images formed under pulsed ruby laser sheet illumination (reference 9). With this technique, JPL was able to measure fuel droplet size distribution and concentration at different fuel flow rates.

This work showed that droplet size distribution was not affected by fuel flow rate but did decrease as airspeed increased. At high airspeeds, the fuel became more finely atomized and flammability increased. Researchers at JPL demonstrated that mist flammability was a function of the Sauter Mean Diameter (SMD) of the fuel droplets. Antimisting kerosene-air mixtures containing fuel droplets with an SMD of 500 microns or more showed a sharp reduction in flammability. They quantified the flammability of flowing fuel droplet-air mixtures by directly measuring the temperature rise in a flame established in the wake of a continuous ignition source.

They also investigated flame spread across a pool of AMK (reference 9). In an impact survivable accident, this can be the critical determinant in the time available for the safe evacuation of passengers. Tests showed no significant differences between the flame spread rates of Jet A and FM-9 AMK across pooled fuel. Both flame spread rates increased with the depth of the fuel layer. When the depth of the fuel layer was increased from 1/8 inch to 3/4 inch, the flame spread rate increased from 2 cm/s to 3.5 cm/s. In fuel pooled over a porous substrate of saturated sand, the flame spread rate for AMK was slightly slower than for Jet A — .41 cm/s versus .53 cm/s.

Results from the spinning disk flammability tester developed by SwRI showed good correlation with the results from FAA's wing-fuel spillage tests when measuring flammability of AMK as a function of FM-9 concentration and simulated air speed or disk velocity (reference 6). In other areas such as the effect of amine in the carrier fluid on AMK flammability, the spinning disk results did not correlate with the results of other flammability tests.

In order to provide its contractors with a standard, small-scale, flammability tester, the FAA Technical Center developed the Flammability Comparison Test Apparatus. Five units were made and calibrated for use in the AMK program (references 23 and 24). In the FCTA, compressed air was released through a sonic orifice. Fuel was injected into the air stream and carried over a propane torch (figure 6).

Results of FCTA tests indicated that the maximum heat output depends on a combination of airspeed and fuel flow rate (reference 8). The FCTA served as a good standard test device for screening antimisting fuel candidates.

In its atomization and flammability study, JPL found that small-scale, flammability tests on units such as the FCTA and the miniwing shear apparatus yielded only an upper bound to the antimisting behavior of AMK (reference 25). In an actual crash, there may be finer misting of a larger proportion of the spilled fuel. The small-scale tests were generally misleading in that they indicated greater fire suppression capability for AMK than the large-scale tests, such as the wing-fuel spillage tests and the catapult tests. The relationships between the small-scale tests and the large-scale tests are shown in figure 7.

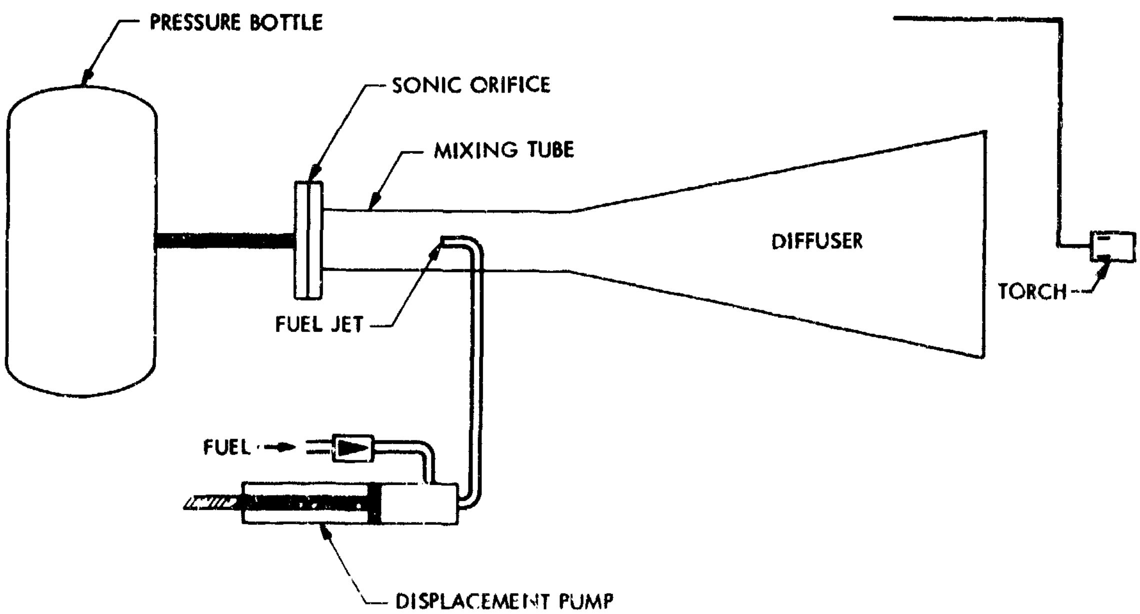


FIGURE 6. FLAMMABILITY COMPARISON TEST APPARATUS

Flammability Comparison Test Apparatus (top), shown with schematic (bottom), was used by FAA and its contractors as a standard test device for screening antimisting fuel candidates.

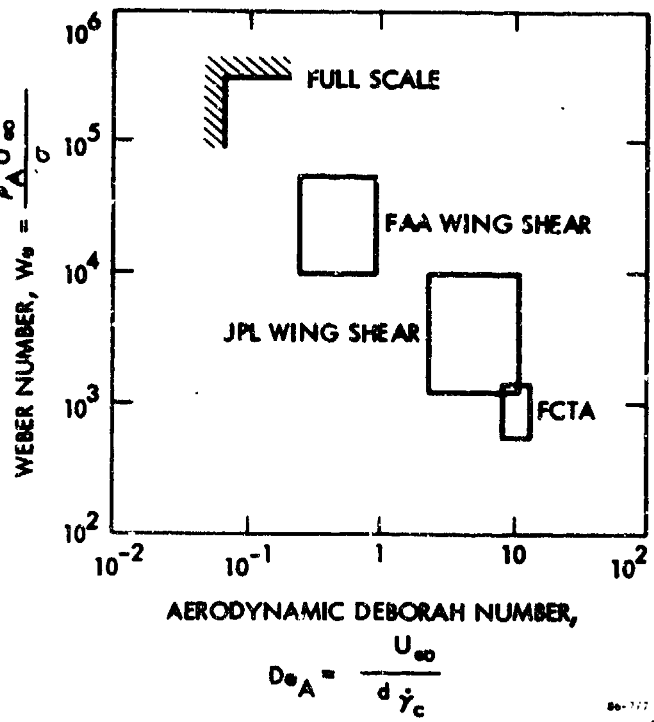


FIGURE 7. CHART SHOWING RELATIONSHIPS OF DIFFERENT FUEL FLAMMABILITY TESTS
Chart prepared by JPL shows the relationship of results from different fuel flammability tests used in AMK program. Weber Number and Aerodynamic Deborah Number are the variables which most affect the external aerodynamics of fuel atomization.

WATER COMPATIBILITY.

If water is added to a tank containing FM-9 AMK fuel, a true solution of water in AMK may occur (reference 26). As more water is added, a micro-emulsion can form in which the particles of water are usually too small to scatter light. Additional water generates coarse droplets and then, a bulk water phase. These phases can occur in combination. The last phase, however, has occurred only in the laboratory and under conditions which were more extreme than worst case flight conditions.

In its study on the effects of water and water vapor on AMK, JPL found that the uptake of water in AMK could be as high as 1,300 ppm at 20° Celsius (reference 27). By comparison, Jet A will hold 56 to 120 ppm at a saturation temperature of 23° C. The way water is introduced into AMK can determine the type and volume of the second phase. Under static conditions, more than 250-300 ppm water are needed to initiate the formation of an insoluble second phase. If the fuel surface is cold, water vapor can produce a precipitate at 150-200 ppm at the fuel-air interface where the local concentration of water is much higher than 200 ppm.

The investigation by JPL showed that the amount of water dissolved in AMK was critically dependent upon external agitation. Therefore, the water absorption limits should be accepted with caution because they probably represent the extreme upper limits. Under realistic conditions, the amount of water which gets absorbed will depend upon local agitation and time.

In addition to water entering the fuel tanks during flight, the most likely sources of water that could come into contact with AMK are free water present in Jet A storage and transfer units and water accidentally introduced into aircraft fuel tanks (reference 8). Large amounts of free water, from 1 to 5 percent, will cause precipitates to form in AMK and must be avoided through good housekeeping procedures, particularly during ground handling and fueling. (Many of the studies on the incompatibility of AMK with free water were done with batch-blended antimisting fuel, but the results appear to be valid for inline-blended AMK as well.)

While water-induced gels in AMK are a recognized phenomenon, there is disagreement over their significance to aircraft operations. In its study of the compatibility of batch-blended AMK with the DC-10/KC-10 fuel system, Douglas Aircraft added water in the form of steam to AMK to produce a total dissolved water content of 250-300 ppm (reference 28). Drops of water collected on a plastic film covering the fuel tank and dropped into the AMK causing a local white contamination which dispersed within one minute. When the AMK was stirred, the contamination dispersed immediately. Upon completion of the water test, Douglas removed and examined the boost pumps used in the test and found no gel or water contamination. Douglas concluded that the small amounts of water would not create any compatibility problems with AMK.

The presence of water in AMK was considered a potentially serious problem by Pratt & Whitney Aircraft (reference 12). Whenever free water was present in AMK, PWA reported, it caused polymer precipitation. The water-induced precipitate clogged filters and was not reversible during subsequent heating cycles. In its initial laboratory deicing test, PWA added water to undegraded, batch-blended AMK to produce a total water content of 210 ppm. After the AMK was degraded, it was passed through a 40-micron filter. Ice formed on the filter causing a pressure rise. The pressure buildup disappeared when the filter was warmed to room temperature.

Then PWA followed its initial test with a full-scale, deicing rig test. A white precipitate formed on the filter paper and couldn't be dissolved by the deicing heater. Subsequent analysis of the AMK showed that the water content had risen to 1,000 ppm, much of which was free water. Pratt & Whitney Aircraft repeated the laboratory test with AMK containing an average of 211 ppm of water in solution. Ice again formed and clogged the 40-micron filter but disappeared upon being heated to 43° C, the typical deicing temperature for the JT8D engine, during the first three icing cycles. On subsequent cycling, the pressure did not return to the original value owing to what PWA believed to be the formation of a flow-induced (rather than water-induced) gel in the AMK.

The FAA believes the validity of these results is questionable because of the procedures used by PWA in its tests. No aircraft would encounter this much water in regular operation, nor would degraded AMK come into contact with free water as in the PWA tests. The results from the Boeing tests on water vapor ingestion under simulated flight conditions were considered more realistic and indicated no water-AMK problems.

In its evaluation of AMK under simulated flight conditions, Boeing conducted several tests on water and water vapor ingestion under worst case conditions. The purpose of these tests was to determine what happens to AMK if airborne water is introduced into the fuel tank ullage through the vent system during aircraft descent through a region of extremely high humidity. The tests demonstrated that the amount of water (approximately 200 ppm) which might accumulate in the fuel

during repeated descents through water-saturated clouds had no adverse effects on the AMK in the tank. Consequently, Boeing reported, ingestion of water vapor in amounts that could be expected in worst case airline service did not appear to cauese special problems with AMK.

MATERIAL AND CHEMICAL COMPATIBILITY.

Compatibility tests on tank sealants and coatings, fuel tank bladder cell materials and fuel system elastomers in contact with antimisting fuels made with FM-9 revealed no problems.

Product Research and Chemical Corporation soaked specimens of its polysulfide sealants and polyurethane coatings in FM-9 AMK at 140° Fahrenheit (F) for 70 days and detected no adverse effects (reference 29). Goodyear Aerospace ran FM-9 AMK compatibility tests on its Vithane BTC69 and nitrile BTC17 bladder materials. Results of these tests showed that the reactions of these materials with AMK were less severe than their reactions with fluids used in military specification tests (reference 30).

Pratt & Whitney Aircraft conducted compatibility tests of FM-9 AMK with typical fuel system elastomers — butadiene rubber and fluorosilicone rubber. They soaked the elastomers in FM-9 AMK for six months and periodically inspected them. At the end of the six month test, PWA found no crack or material crazing in any of the test specimens (reference 12). The measured mechanical properties stabilized after one week of soaking.

They also investigated the compatibility of FM-9 AMK with different chemical additives routinely used in jet fuels (reference 12). These were: Hitec E515, a corrosion inhibiter/lubricity agent; JFA5, a thermal stability improver; Biobar JF, a biocide; ethylene glycol-monomethyl ether, an anti-icing agent; and N,N'-disalicylidene 1,2-propane-diamine, a metal deactivator. All additives except the anti-icing agent were blended with undegraded, batch-blended AMK in amounts 10 times those normally used and then observed for five days. The anti-icing agent was tested at the recommended allowance.

The metal deactivator produced no observable reaction. The corrosion inhibitor/lubricity agent showed a slight turbidity after one day. The thermal stability additive produced a small amount of particulate precipitate after four days as did the Jet A control sample. The anti-icing agent produced a lacy deposit. The biocide deposited a film on the wall of the test vessel after four days.

In a second test, PWA blended the additives with undegraded AMK in the recommended allowable amounts. The anti-icing agent was the only one to produce a precipitate, a lacy deposit as in the first test. The metal deactivator formed a small amount of precipitate in the control sample of Jet A but produced nothing in the AMK.

Pratt & Whitney also measured the effect of AMK on light, copper turnings for 48 hours. Test results indicated that copper was more reactive with AMK than with Jet A. However, bronze parts of a fuel pump used for more than 100 hours in the program showed no adverse effects from AMK, whether this would be significant over the long term is unknown. In its fuel analysis and quality control tests, PWA measured 3.4 to 3.7 ppm of sodium in six blends of AMK. These levels of sodium would appreciably accelerate hot-section corrosion in a jet engine. However, Imperial Chemical Industries informed the FAA that it planned to change the process

used in making FM-9 powder in order to eliminate the sodium (reference 31). Samples of sodium-free AMK were later provided by ICI and tested by FAA on the Technical Center wing-fuel spillage facility. The sodium-free AMK provided the same fire protection capability as the regular AMK.

An investigation was undertaken by ICI into AMK's compatibility with Jet A (reference 32). In earlier laboratory and field test work, both FAA and ICI encountered a gel that formed when AMK came into contact with residual Jet A or when Jet A was added to AMK. They reported that when the mixed fuel was used in a small pump-degrader system, gel could be formed due to shearing action. There appeared to be no problem when the AMK proportion was greater than 50 percent or if the dilution was done with degraded AMK or Jet A treated with glycol. Both ICI and FAA agreed that this gel formation due to shearing mixtures of Jet A and (less than 50 percent) AMK posed a potentially serious operational problem and would require further study.

ALTERNATE ADDITIVES.

For the AMK development program, the FAA had asked ICI to freeze the formula for its antimisting slurry in August 1983. The composition agreed to at that time was a 25 percent concentration of FM-9 in a glycol amine carrier fluid. This was the formulation that was used in the subsequent development and test programs in the United States and United Kingdom. On its own, ICI continued to develop new FM-9 compositions. The FAA and its contractors tested some of of the new ICI compositions as well as additives supplied by Arco, Conoco, and Dow (references 33 and 34). A polyisobutylene produced by BASF was also tested as part of work on a cryofracturing blending process. No large-scale flammability tests were run on the polyisobutylene because of its known low temperature pumpability problems.

The Arco, Conoco and Dow additives passed the laboratory-scale FCTA tests and were tested on the large-scale, wing-fuel spillage facility. The Conoco and Arco additives showed sufficient fire protection potential to warrant further testing with regard to their cold flow and pumpability characteristics. Low temperature pumpability tests on the Arco and Conoco additives using a small Cessna 441 boost pump (reference 34) were run by JPL. Both additives displayed unacceptable low temperature pumpability. But JPL also found that the low temperature pumpability of inline blended FM-9 AMK was unacceptable with the small Cessna boost pump. Using a DC-10 boost pump with a much higher flow rate, JPL obtained acceptable low temperature pumpability results with FM-9, indicating that pump size or configuration has an yet undefined effect. Similar results in the DC-10 boost pump might be obtained with the Arco and Conoco additives.

AMK PRODUCTION.

Early in the AMK program, researchers recognized the desirability of blending antimisting additives into jet fuel at the aircraft fueling point (references 35 and 36). Introduction of the additive at an earlier stage would increase costs, unintentional degradation, and the possibility of contamination (reference 37). But it was not until late 1983 that FM-9 antimisting additive became available as a slurry suitable for inline blending.

The slurry developed by ICI consisted of 25 percent (by weight) FM-9 powder dispersed in a carrier fluid of glycol, amine, and water. Prior to this time, FAA and its contractors worked with batch-blended AMK (Jet A mixed with FM-9) supplied by the manufacturer, or they blended AMK using FM-9 powder supplied by ICI. The

batch-blended 0.3 percent FM-9 AMK comprised 0.3 percent (by weight) FM-9 polymer, 0.6 percent (by weight) glycol/amine carrier fluid, and 99.1 percent (by weight) Jet A.

Most of the rheological and characterization data on AMK resulted from the early work with batch-blended fuels. Researchers later found that certain AMK characteristics such as filterability and low temperature pumpability differed significantly in batch-blended and inline-blended AMK (references 10 and 38).

The FAA and its contractors worked extensively on the development and optimization of inline blending of AMK (references 39, 40, and 41). This work yielded four inline blenders with capacities of 1 liter/minute, 10 gallon/minute, 25 gallon/minute and 50-125 gallon/minute (figure 8). All the blenders follow the same basic design. To insure precise flow control, a variable speed, progressive cavity pump is used to pump and meter the FM-9 slurry. The metered slurry is injected into the Jet A stream immediately upstream of the static mixing tube. Jet A is supplied to a flow control device by an external pump in the 125 gal/min blender. The flow controller, over a limited pressure range, automatically adjusts to changes in system and inlet pressures to assure a constant, preset flow rate.

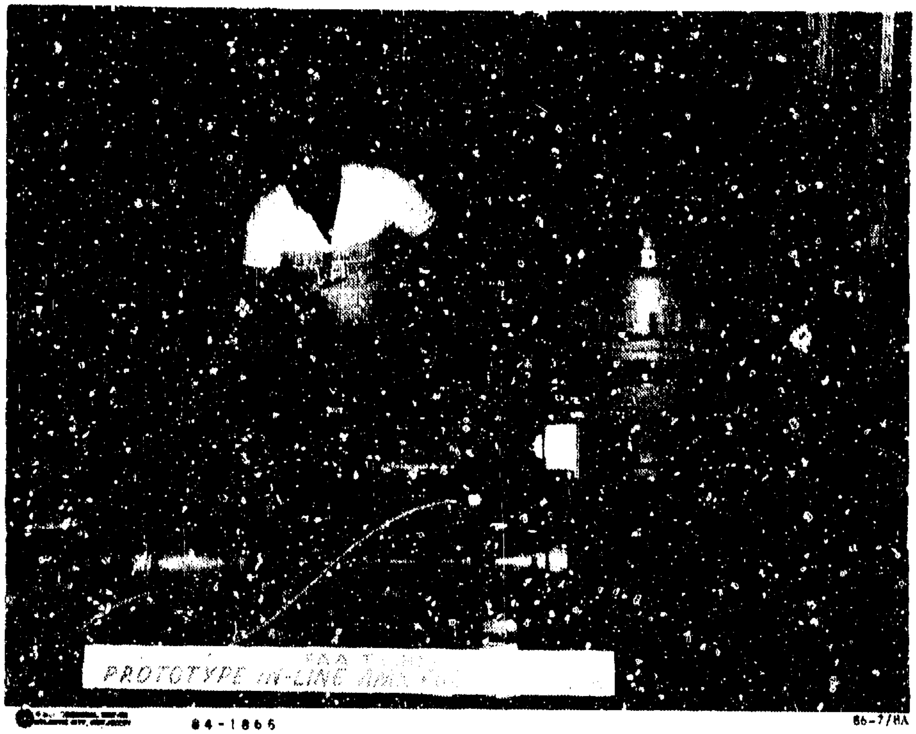
After the FM-9 slurry is added to the Jet A stream, the blended fuel passes through static mixing tubes. These tubes rely on a combination of high fluid Reynolds number and fluid residence time to blend the slurry and Jet A into a homogenous fluid. The degree of dispersion and blending achieved by the static mixing tubes determines the antimisting polymer's dissolution in the Jet A and, therefore, is an important factor in blending high quality AMK fuel. The properties of the slurry — chemical and physical — are also an important factor in determining the quality of the blended antimisting fuel.

Based on its experience gained in this program, FAA established the specifications shown in table 1 for inline blended FM-9 AMK (reference 42). Work by JPL with different Jet A base fuels showed that only the fuel's aromatic content significantly impacted the final characteristics of the blended antimisting fuel (reference 39).

TABLE 1. AMK SPECIFICATIONS

FM-9 Polymer	0.30% ± 0.02% By Weight (ASTM D 381)
Clarity*	20 Ntu (Max.)
Orifice Flow Cup*	2.5 Ml/30 Sec. (Max.)
Filter Ratio*	35-100
Total Water	230 PPM Max. (ASTM D 1744-64)
Appearance	Uniform; No Visible Sediment
Stability	6 Months (Min.)
Jet A Base Fuel	Commercial Grade (ASTM D 1655)
	Aromatics 12% (Min.)
	Total Water 80 PPM Max. (ASTM D 1744-64)

*30 Minutes After Blending



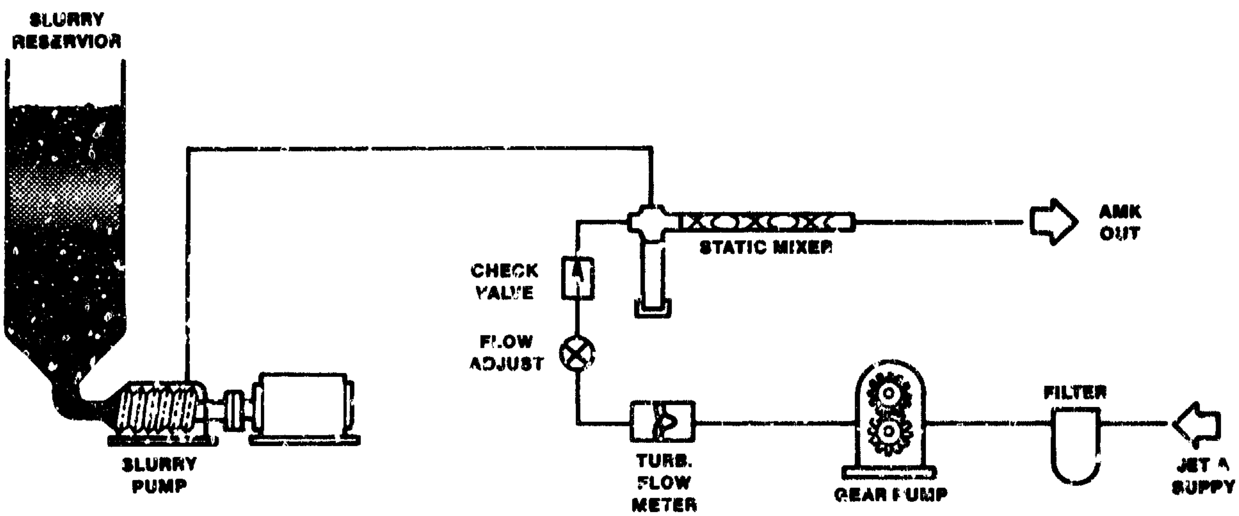


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FIGURE 8. PICTURE AND SCHEMATIC OF INLINE BLENDER
Largest of the four inline blenders developed by FAA and its contractors, the 50-125 gallons/minute unit (top) was used to blend AMK for the CID B-720 aircraft. All blenders worked on the same principles illustrated by the schematic (bottom).

ICI Americas produced Avgard™ (registered tradmark of ICI) slurry in 240-pound (maximum) batches and delivered it in sealed containers holding 40 pounds of slurry. ICI provided an analysis for each batch of slurry that had to meet the specifications listed in table 1.

Blending studies by the RAE and JPL demonstrated that freshly inline blended FM-9 AMK fuel developed adequate fire resistance after a 15 to 20 minute aging period, provided that the temperature at blending and the aromatic content of the fuel were not too low (references 8 and 39). When the temperature was below 0° C and the aromatic content of the base fuel was below 12 percent, polymer particles tended to settle out.

In some early studies, filter ratio results indicated that freshly inline-blended FM-9 AMK appeared to be more difficult to degrade than batch-blended fuel, which had time to equilibrate (references 43, 44, and 45). Both JPL and SwRI, for example, degraded samples of the equilibrated batch-blended and freshly inline-blended FM-9 AMK and then conducted filter ratio tests on the degraded fuel samples after they had cooled to ambient temperature. The inline-blended fuel samples yielded filter ratios 10 to 20 times higher than the batch-blended samples. Despite the differences in their filter ratios, in simultaneous degradation-filtration tests, all the fuel samples passed through square mesh, metal filters of 40 to 200 microns without plugging. Filter ratio measurements don't always give a valid indication of fuel degradability. In its characterization of degraded AMK, JPL noted that often with freshly blended AMK there would be undissolved polymer that was not degraded (reference 45). Consequently, if filter ratio tests on these samples were not run within one minute after degradation, the undegraded polymers would swell, producing high filter ratio readings.

ICI and others worked on ways of accelerating the dissolution of the FM-9 antimisting polymer in jet fuel in efforts to reduce the equilibration time and the power required to degrade inline-blended AMK (references 33 and 46). In March 1983, ICI developed a new slurry with a higher solid loading that had excellent dissolution properties. In tests at FAA, ICI, and the RAE, AMK fuel made from this slurry successfully demonstrated fire resistance properties and degradability within 15 minutes of blending. Because the slurry was available only in limited quantities, it was not used in FAA's full-scale validation program.

The FAA sponsored studies at JPL on the effects of different base fuels on the properties and performance of antimisting fuels (reference 39). Researchers from JPL found significant differences in a limited sampling of the Jet A base fuels. But with the exception of aromatic content, which had to be at least 12 percent, these variations did not significantly affect AMK characteristics.

A study was conducted by JPL for the FAA on the problems associated with inline blending AMK at different base fuel temperatures (reference 47). Using a 1 liter/min blender, JPL researchers made a series of AMK blends with the Jet A base fuel at different temperatures from -35° C to 40° C. From these tests, JPL concluded that the optimum blending temperature range for AMK was between 0° C and 30° C. When blended with a base fuel above 30° C, AMK lost some of its fire protection capabilities; and above 33° C, it lost all fire protection properties. The JPL researchers also found that when AMK was blended at temperatures below 0° C, the dissolution rate for the polymer was too slow for the fuel to develop antimisting properties within the goal of 15 to 20 minutes after blending.

In another FAA sponsored study, General Technology Applications, Inc. (GTA), investigated its cryofracturing process as a method for rapidly dissolving antimisting additives in Jet A (reference 33). This process used a hammer mill cooled by liquid nitrogen to break intramolecular bonds and produce active surfaces on polymer particles which would interact with liquid hydrocarbons to accelerate dissolution. The process worked well in blending Jet A and Oppanol B-230, a high molecular weight polyisobutylene polymer with time dependent solubility and antimisting properties. But attempts to blend Jet A and FM-9, which was supplied as a fine powder, were unsuccessful.

AMK DEGRADATION.

As part of the AMK safety work, FAA demonstrated in limited tests that jet engines could operate on undegraded antimisting fuel. But studies in the United States and United Kingdom clearly showed that for modern jet engines to start and to operate efficiently and cleanly on AMK, the FM-9 antimisting polymer must be highly degraded to restore the AMK as closely as possible to Jet A properties prior to combustion.

The relationship among degradation levels, fuel atomization and combustion efficiency and stability were investigated by JPL (reference 48). Their researchers used a fuel nozzle from a PWA JT8D engine to produce AMK sprays at flow rates corresponding to engine ignition, idle, cruise, and takeoff conditions. They tested Jet A (FR = 1), undegraded AMK (FR = 30), and degraded AMK with filter ratios of 1.2, 1.3, 1.5, 1.6, 6.6 and 20.

At all power settings, JPL found that combustion efficiencies decreased with increases in filter ratio. Also, unburned hydrocarbons and carbon monoxide emissions increased with increases in filter ratio and droplet sizes. For AMK, with a 1.2 filter ratio at idle, combustion efficiency dropped to 99 percent from 99.3 percent with Jet A. Combustion efficiency dropped further to 97.9 percent when the filter ratio rose to 1.5. These results confirmed those obtained earlier by PWA and Lucas Aerospace (references 13 and 49).

The FAA and RAE and their contractors investigated various methods for degrading AMK. All of them produced a net energy loss to the engine cycle. In any future designs, however, the degrader would be designed as an integral part of the engine fuel pump and control system to keep weight and energy penalties to a minimum.

In work for the RAE, Plessey Aerospace Ltd. developed a combined pump-degrader based on the BP 240 main engine fuel pump from the Phantom-Spey aircraft (references 50 and 51). Plessey tested the unit at rotational speeds of 5,000 to 12,000 rpm and at fuel flow rates from 0.505 to 1.26 liters/s. At a specific power of 63 kw/liter, it degraded AMK in a single pass to 1.4 filter ratio from 24. The large power requirement of the pump-degrader led Plessey to conclude that a systems approach would be highly desirable in order to take advantage of the degradation provided by other components such as boost pumps.

Plessey, along with PWA and JPL, investigated nonmechanical means for degrading AMK including ultraviolet light, catalysis, ultrasonics, lasers, cavitation and centrifuges. Plessey concluded that the nonmechanical methods were ineffective, too slow, or not suitable for aircraft operations (reference 50). Commercial cavitation devices were used by PWA to degrade AMK successfully, but size and power requirements precluded their use in aircraft (reference 12). Both PWA and United Technologies Research Center believe, however, that AMK can be degraded adequately

with a multistage cavitating venturi based on results of tests with a single-stage unit (reference 52).

In the United States, SwRI developed a hydromechanical degrader that used a variable flow pump to raise AMK to high pressure ([illegible],000-4,000 psi) and force the fuel through flow restrictors — packed beads, metal screens or a needle valve — to degrade the antimisting polymer (reference 6). Working with batch-blended fuel, SwRI was able to achieve filter ratios of 1.2 in a single pass through its degrader at a specific degrader power of 15 kw/liter (reference 53).

The SwRI degrader used an axial piston pump from a TF30 engine driven by a 50 hp electric motor through a magnetic coupling device. A needle valve, located immediately downstream of the pump, acted as a variable area orifice to maintain a constant pressure drop over a wide range of fuel flow rates. The speed limitation of the electric motor restricted the maximum flow rate to about 1,500 kg/hour, which represented cruise conditions for the JT8D commercial engine.

With this degrader, SwRI evaluated the filtration performance of degraded AMK with filters from the JT8D and CF6 engines. The filters were located immediately downstream of the needle valve degrader. The results showed that AMK degraded at a specific power of 21 kw/liter could flow through these filters under cruise conditions at pressures close to those for Jet A. The results remained virtually the same when degrader specific power was reduced to 14 kw/liter. But when the temperature was lowered below 0° C, specific degrader power had to be increased to 29 kw/liter to produce satisfactory filter performance (reference 6).

In later work with inline-blended AMK, SwRI found that it appeared to be more difficult to degrade freshly inline-blended fuel than equilibrated batch-blended fuel (reference 11). At the same specific power, the needle valve degrader achieved a filter ratio of 10 for the inline-blended fuel and 1.2 for the equilibrated batch-blended fuel. But critical velocity measurements made by SwRI in its degradation-filtration tests indicated that the inline-blended AMK was only slightly more resistant to degradation than the fully equilibrated batch-blended AMK. As discussed earlier in the section on AMK production, indicated filter ratios for freshly inline-blended AMK are misleading.

For its degradation studies, JPL used a needle valve degrader similar to one used by SwRI (reference 54). It demonstrated that fresh, inline-blended AMK could be degraded and filtered through a 325 mesh wash flow filter within 20 minutes of blending at 20° C. A specific degrader power of 27.6 kw/liter was used. Pressure drop across the degrader was 4,000 psi. But when the temperature was lowered to -20° C, the AMK, degraded at the same specific power of 27.6 kw/liter, failed the filterability test.

In later work on the degradation of cold, freshly inline-blended AMK, JPL modified the degrader by adding a recirculation loop, a bypass loop heater, and a counterflow heat exchanger to heat the incoming, cold AMK (reference 47). These modifications, according to JPL, greatly improved the low temperature performance of the degrader. For a 38 percent recirculation and a 4,000 psi pressure drop across the needle valve, the degrader power requirement was 44 kw/liter.

General Electric (GE) developed a prototype flight degrader for the FAA based on the high speed, augmentor centrifugal pump for its military F101 engine (references 55 and 56). In bench tests, the GE unit degraded inline-blended AMK to high levels

(FR = 1.2) over a full range of flow conditions. The specific fuel consumption penalty for engine gear box power to operate the pump-degrader, according to GE, would be relatively low. The unit was flown on the No. 3 engine of the CV-880 flight test vehicle (figure 9) and was used on all four engines of the Controlled Impact Demonstration (CID) B-720 aircraft (figure 10).

The test conditions specified for the GE degrader were based on the requirements of the GE CJ805 and the PWA JT3C engines used, respectively, in the CV-880 and B-720. In terms of flow capacity, the GE/F101 pump-degrader was considerably oversized for the CV-880 engine, which required up to 30 gal/min, maximum. (The only high speed, centrifugal pump immediately available, the F101 augmentor pump was designed for a 210 gal/min flow rate on jet fuel.) Consequently, the power required to operate this degrader was considerably higher than it would be for a degrader specifically designed for the application. General Electric estimated that a new, high speed, centrifugal pump-degrader designed for its CF6-80 would require an input power of only 25.7 shp at cruise compared to the 41 shp required for the gear pump currently used on this engine (reference 55).

UNDEGRADED AMK PERFORMANCE.

Prior to the impact demonstration, the FAA Technical Center conducted several engine tests on undegraded AMK fuel (references 57, 58, and 59). The engines were started on Jet A fuel and then switched to undegraded AMK without any operational problems. In one test, an engine ran continuously on undegraded AMK for approximately three hours. The engines were able to operate at rated thrust despite significant reductions in efficiencies which resulted apparently from the poor atomization of the undegraded fuel. Test results showed increases in thrust specific fuel consumption as high as 7 percent for engines operating at cruise conditions on undegraded AMK.

The FAA Technical Center ran a series of ground tests in 1982 using a YTF30-P1 engine fueled with batch-blended, undegraded FM-9 AMK (references 57 and 58). The engine's afterburner was replaced with a straight, conical exhaust collector and nozzle. In each test run, the engine was started and brought to idle on Jet A and then switched over to undegraded AMK. The engine was operated from idle to full power with accelerations and decelerations for a total running time of 2 hours and 57 minutes.

Following the initial run on undegraded AMK, the engine's thermodynamic performance deteriorated somewhat. The high pressure compressor had to be operated at higher speed to achieve the same pressure ratio; and the speed match between the high and low pressure rotors shifted. Turbine discharge temperatures also increased, indicating a possible deteriorated turbine condition; and the manifold pressure produced at a given drive speed dropped. These conditions are believed to have resulted from the shear thickening characteristics of AMK which produced poor nozzle spray patterns, with the flame front moving closer to the turbine inlet stages.

In support of the CID, the FAA Technical Center conducted tests with a PWA JT3C-6 engine operating on inline-blended, undegraded AMK (reference 59). The engine's fuel control system was modified to correspond to the more stringent conditions of the JT3C-7 engines installed in the B-720 CID aircraft. The tests were designed to duplicate the conditions expected during the final CID flight to determine what would happen if the engine degraders failed. A total of 1,348 gallons of AMK were

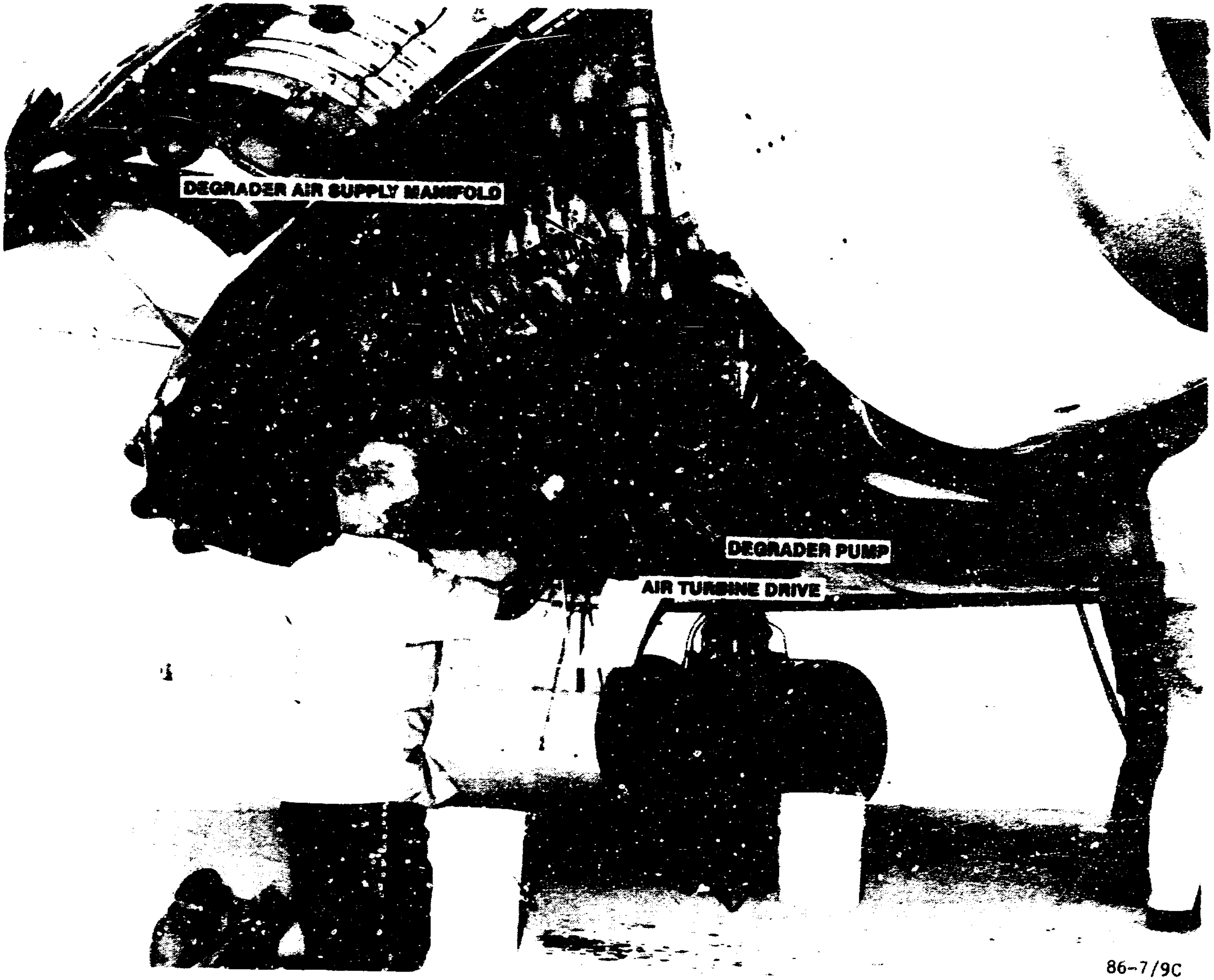

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FIGURE 9. DEGRADER INSTALLED ON CV-880 AIRCRAFT
On the CV-880 flight test aircraft a single prototype degrader was installed in the 6 o'clock position on the No. 3 engine.

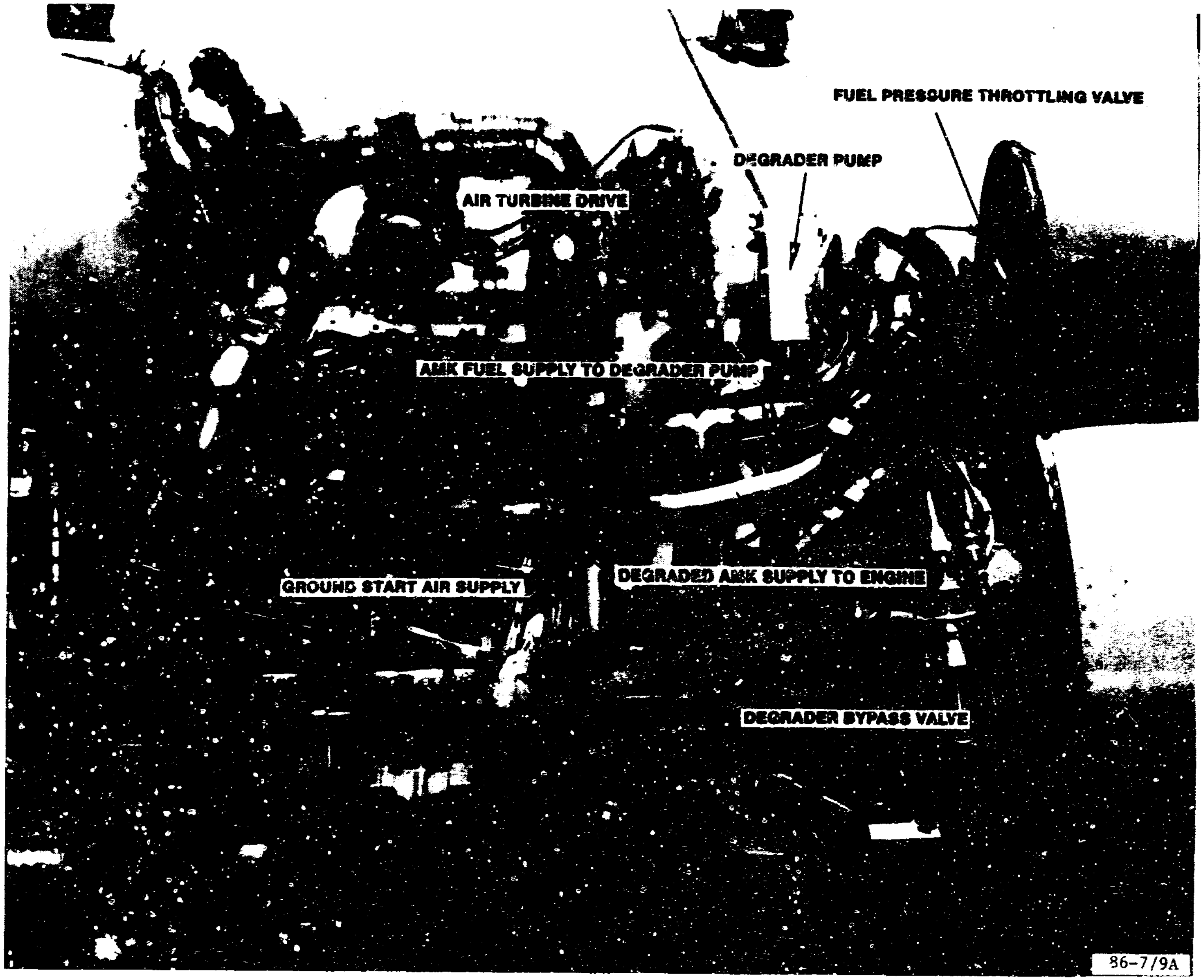


FIGURE 10. DEGRADERS INSTALLED ON B-720 AIRCRAFT
Prototype flight degraders were installed on top of all four engines in the B-720 CID aircraft

blended directly into the B-707 wing tank of an integrated, aircraft fuel system rig at the Technical Center and then fed to the engine in the test cell by the wing tank boost pump. The engine, which was started and shut down on Jet A, operated on the undegraded AMK for 2 hours and 17 minutes.

Pretest and posttest calibrations of the engine on Jet A for these tests showed no significant differences in engine operating characteristics. The speed match between the high and low pressure compressors remained the same as did pumping characteristics and fuel flow requirements. Nor were there any significant differences in the engine's acceleration-deceleration characteristics before and after the test on undegraded AMK. No operational problems were encountered during the simulated CID mission or during a subsequent one hour endurance run on undegraded AMK. Differential pressures across the fuel filters did rise but stabilized. Following the tests, all fuel filters were removed and examined. All were clean and showed no trace of contamination or gel. However, no teardown inspections were conducted.

Prior to the CID simulation, the Technical Center, in 1982 and 1983, had accumulated approximately one and a half hours experience running two PWA J60-P-6 engines on undegraded, batch-blended AMK. The engines were started on Jet A, then switched to undegraded fuel at idle before being run up to cruise power. No operational problems were encountered. The two J60 engines were then mounted on the aft fuselage of a surplus RB-66 aircraft that was crash tested on a Naval Air Engineering Center catapult in April 1983 (reference 21).

LOW TEMPERATURE BEHAVIOR.

Because jet fuel is routinely exposed to extremely low temperatures in aircraft wing tanks during flight as well as in above ground fuel storage tanks in some northern countries, FAA contractors studied AMK's low temperature behavior.

The Boeing Company studied the use of AMK in airframe fuel systems and in certain critical engine components (reference 60). Boeing used a 50-gallon B-747 wing tank, cold fuel simulator for environmental and component tests (figure 11). For the long term (2-hour) performance tests, the Boeing Fuels Laboratory assembled a simulated B-767 aircraft fuel feed system.

Boeing began its test program with batch-blended fuel but switched to inline-blended AMK when it became available. For blending and degrading the antimisting fuel, Boeing used a 25-gal/min blender and the SwRI needle valve degrader, both supplied by the FAA Technical Center.

Boeing's test plan called for the study and evaluation of the following:

- o Differences between AMK and Jet A on a simulated, commercial, airplane flight under worst case, low temperature conditions.
- o Effects of repeated thermal cycling and airframe motion on the antimisting characteristics of AMK.
- o Effects of water and water vapor ingestion on AMK under worst case humidity conditions during flight.
- o Performance of production, fuel system components such as boost pumps, jet pumps, engine driven pumps, and capacitance quantity gauges with AMK.

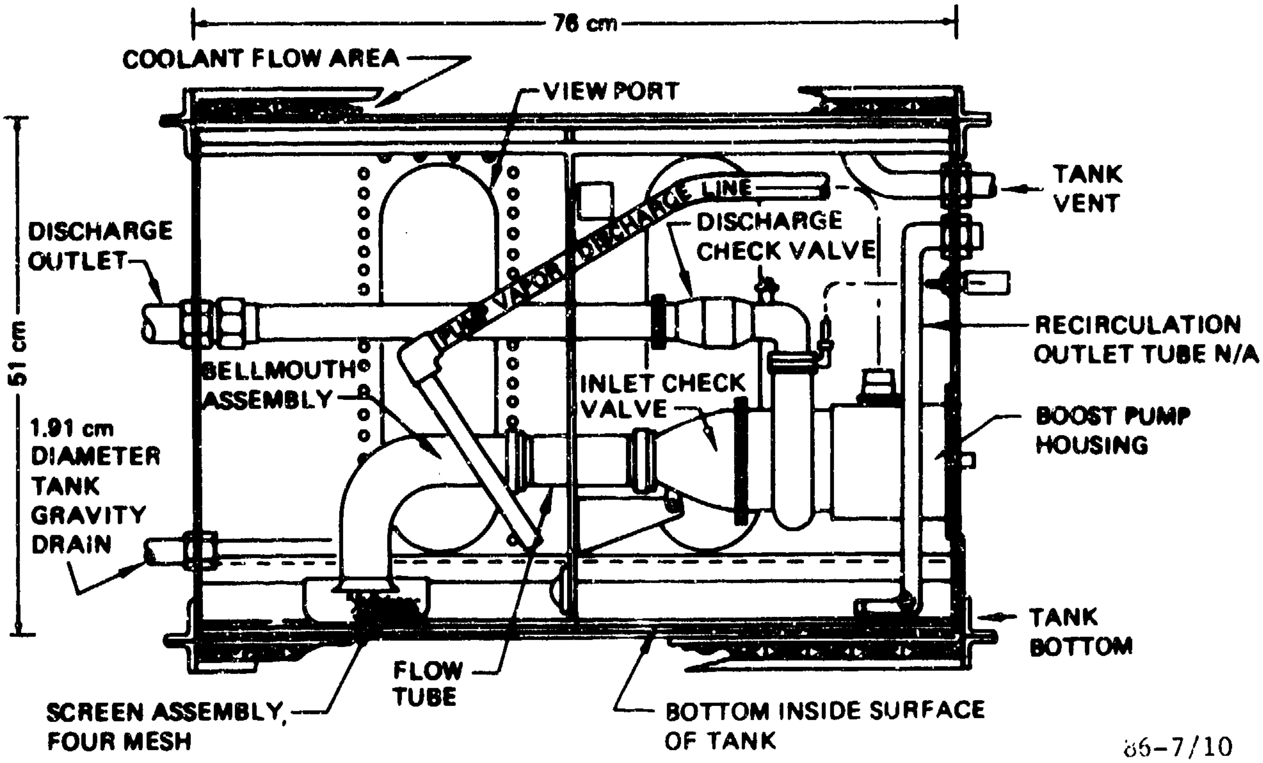


FIGURE 11. INTERIOR OF COLD FUEL SIMULATOR TANK
Drawing shows the interior of the 50-gallon cold fuel simulator tank used by the Boeing Company to conduct low temperature, dynamic simulation tests on AMK.

o Continuous, long-time performance of a commercial aircraft boost pump with cold AMK.

Later, the FAA added the following secondary objectives to the Boeing program:

o Power requirements for degrading AMK at low temperatures.

o Long-term performance of typical, engine, fuel feed system filters with cold AMK.

Boeing compared the bulk fuel cooldown rate of AMK with that of Jet A and found no major differences in the thermal responses of the two fuels. At -40° C, Boeing noted, the Jet A turned an opaque yellow while the AMK remained clear. During boost pump operation, semitransparent strands of gel formed on the free surface of AMK and on the interior surfaces of the tank at temperatures of -20° C and below. A result of the boost pump vapor discharge jet interacting with the AMK, the strands of gel dissolved back into the fuel as temperatures approached ambient and never interfered with boost pump operation.

Boeing observed the formation and disappearance of similar, transparent strings of gel during its thermal cycling tests. Visual inspection of the fuel tank after it was drained showed no gel deposits on the interior surfaces. Designed to determine the effects of repeated thermal and dynamic cycling on the antimisting characteristics of AMK, the tests showed that AMK retained its antimisting properties after exposure to a severe, low temperature, flight profile with and without slosh and vibration, and even after repeated 6-hour thermal cycles between 55° C and -60° C skin temperatures. (When the skin temperature was -60° C, the bulk fuel temperature was -48° C.)

Boeing concluded that the antimisting properties of AMK are not adversely affected by low temperature exposure nor by normal airplane flight dynamics and vibration exposure.

Existing heat transfer calculation methods can be used to calculate AMK temperatures in fuel tanks, according to Boeing. When subjected to low temperature environments, AMK displayed essentially the same thermal response as Jet A. This means that existing models used to analyze buoyantly driven (free convection) heat transfer properties of Jet A can be applied to the same systems operating with AMK. This finding is contrary to that for forced convection, Boeing said, where AMK is a less effective heat transfer medium.

Boeing also empirically developed vertical tank temperature profiles for Jet A and AMK. These profiles were generally the same. Boeing also found that the bulk fuel cooldown rates of AMK and Jet A showed no major differences in thermal response.

Overall, Boeing reported that its environmental and component performance tests revealed no insurmountable problems with airframe fuel system components operated with AMK over the temperature range and number of cycles studies. Boeing did encounter problems with airframe suction feed, jet pump performance and engine fuel filters. These problems are discussed later under "Component Compatibility."

JPL investigated the low temperature behavior of both batch- and inline-blended AMK (references 27, 38, and 54). In its early work with batch-blended AMK, JPL observed that a relatively stable, shear-induced gel formed in AMK at -30° C, causing a reduction in flow performance. Their researchers also noted that water vapor from humid air condensed and froze on the surface of cold fuel. When the cold fuel was AMK, the condensation-freezing process could result in polymer separation and the formation of a white precipitate which floated on the surface of the AMK. Although these results caused concern initially among JPL researchers, they never did materialize as serious problems in the lab's later work with a low temperature simulator and inline-blended fuel or in operational use in the CV-880 aircraft.

For its low temperature studies of inline-blended AMK, JPL used a 50-gallon, wing tank simulator in which the top and bottom surfaces were cooled by the circulation of chilled methanol. The cooling process was controlled to maintain the bottom surface temperature close to one of the three temperatures (-40° C, -45° C, and -50° C) selected for the tests. The cooldown process took five and a half hours during which 12 temperatures were recorded every 10 minutes. The cooldown and freezing behavior of AMK and the Jet A base fuels at the selected temperatures were evaluated and compared by JPL.

From these tests, JPL established vertical temperature profiles for the different AMK and Jet A samples (reference 38). The results of these tests showed that AMK cooled somewhat more slowly than Jet A and that the amount of cold fuel holdup (amount of fuel left in the tank) was slightly less in the case of AMK. Rocking the simulated wing tank, said JPL, did not significantly alter the cooldown or freezing behavior of the fuels. It also undertook an evaluation and comparison of the performance of fuel boost pumps with low temperature AMK and Jet A. The results of this work are discussed later in the "Component Compatibility" section.

Using a needle valve degrader with a 4,000 psi differential, JPL degraded inline-blended AMK at 20° C within 12 minutes and successfully passed it through a 325-mesh screen without plugging. However, when the fuel was cooled to -22° C, the filter screen plugged immediately (reference 61). For inline blending of AMK, JPL reported that the base jet fuel should be between 5° C and 30° C. With base fuel below 5° C, AMK takes 45 minutes or longer to develop adequate fire protection. If blended with fuel above 30° C, AMK loses its antimisting properties.

COMPONENT COMPATIBILITY.

The FAA and the Royal Aircraft Establishment conducted extensive testing on the compatibility of AMK with aircraft and engine fuel systems and components. (All of these tests were of limited duration, however, and a service test and evaluation program would be needed to identify any long term operational problems.)

The Boeing program emphasized fuel system component operation at simulated environmental extremes (reference 60). The AMK fuel was exposed to severe low temperature flight profiles with slosh and vibration, repeated thermal cycling, a "worst case" vent/ullage water vapor environment, suction feed at cold temperatures and altitude extremes, and boost pump delivery at cold fuel temperature extremes.

In the case of its B-747 main boost pump, Boeing found that the pump performed satisfactorily with AMK at ambient, -20° C and -40° C. At all temperatures, the pump required more power to pump AMK than Jet A. But as the temperature decreased, pumping efficiency increased with AMK and decreased with Jet A. The temporary appearance of gel due to the interaction between the vapor/liquid discharge jet and the surrounding AMK caused no problems.

To get more data on boost pump operation than was possible with the limited capacity of its 50-gallon cold fuel simulator, Boeing conducted a 2-hour endurance test on a simulated B-747 feed system using 2,000 gallons of fuel at the temperature desired. In this test, Boeing used a B-747 override boost pump similar to the main boost pump but with higher capacity and pressure output. This time, the pump used approximately the same power to pump AMK as Jet A at ambient and at -20° C and less at -40° C. The reason for this anomaly, Boeing suggested, might be the higher pressure and flow rate developed by the override pump compared to the main boost pump.

During the 2-hour endurance test with AMK, Boeing observed gel formations on the downstream side of the filters used in the feed system simulator: a JT8D fuel control wash filter, a JT9D interstage filter, and a CF6 low pressure cartridge filter. There was a slight pressure rise across the interstage and washflow filters at ambient temperature; a higher pressure rise at -20° C; and at -40° C, the filters bypassed within a few minutes. The experimental needle valve degrader used by Boeing for the tests was not designed for use with low temperature AMK.

With a suitable degrader, it is unlikely that Boeing would have encountered the gel buildup on the downstream side of the filters.

Boeing also ran cold fuel performance tests on a jet pump used in the B-747 to scavenge water from low points in the main fuel tanks. Jet pump performance was substantially lower with AMK than with Jet A at ambient temperature and at -20° C and approximately the same at -40° C. While AMK's high affinity for water may eliminate the need for a continuous water scavenge system, jet pumps will continue to be used in some aircraft for fuel transfer as well as water scavenge and would probably have to be redesigned for AMK applications.

In its investigation of jet pump performance with AMK, JPL used mostly batch-blended fuel and, later, a limited amount of work was done with inline-blended AMK during a performance improvement study (reference 62). Results of JPL's investigation were similar to those of Boeing. They found that jet pump performance with undegraded AMK was reduced as much as 50 percent compared to its performance with Jet A. The cause of this poor performance, according to JPL, is the suppression of turbulent mixing by AMK. They also found that jet pump performance with AMK improved at lower temperatures.

To improve jet pump performance with AMK, JPL suggested that the length of the constant area section of the pump be increased by a factor of four to provide a mixing chamber length-to-diameter ratio of 20:1 compared to the present ratio of 5 or 6:1 used in jet pumps. With increased mixing chamber length, JPL obtained a 15 percent improvement in mass transfer rate at a 2 psi pressure head. An alternative approach would be to use larger jet pumps. They also found that priming jet pumps with AMK was more sluggish than with Jet A. Air bubbles became trapped in the lines, and the pump was slow to start.

As part of this program, JPL researchers evaluated the effect of water ingestion by jet pumps on performance and on the physical characteristics of AMK (reference 62). They operated a jet pump at an induced flow rate of 0.5 gallons/minute and a total flow rate of 1.5 gallons/minutes. At a water flow rate of 2 cc/sec., this produced a water concentration of 6.3 percent in the induced flow line and 2.1 percent in the total flow line. Despite the higher concentration in the induced flow line, the water remained in the form of small droplets. But in the total flow line, phase separation occurred. A white precipitate formed on the inside surface of the pipe and was carried into the collecting tank.

The tests showed that large amounts of bulk water could be in contact with AMK without forming a precipitate or emulsion. Once the water-AMK mixture entered the pump, however, large amounts of precipitate formed as a result of the pump's agitation or mixing action. Although this precipitate did not impair pump performance or the fuel's antimisting property, the long term accumulation of this precipitate might affect other fuel system components and warrants further study.

In early tests, Lockheed-Georgia Company used a full-scale C-141 aircraft fuel system simulator to evaluate system and component performance with FM-9 AMK which was batch blended without carrier fluid (reference 63). Lockheed simulated a typical aircraft flight profile with the tank-to-engine fuel feed system operating. In addition to the fuel feed system, Lockheed evaluated the tank quantity gauging system accuracy, tank refuel valve operation and fuel transfer, ejection pump performance.

Results of the Lockheed tests showed that AMK was compatible with capacitance gauges and did not introduce any errors into the measurement system. Use of AMK did reduce the performance of the fuel tank boost and ejector pumps. Although the engine fuel pump operated satisfactorily without a degrader, the engine's 10-micron filter was bypassed during simulated takeoff and cruise fuel flow conditions due to a pressure buildup across the filter of more than 12 psi. Post-test inspection of the filter showed no accumulation of AMK gel or foreign matter. Lockheed tests also showed increases in fuel transfer and fuel level control valve closing times with AMK.

Douglas Aircraft Company evaluated the use of AMK using a KC-10/DC-10 fuel system simulator (reference 28). Working with batch-blended AMK, Douglas ran four simulated flights, a simulated aerial refueling, and tested the effects of water in a tank of AMK. All the KC-10/DC-10 tests were conducted at sea level, ambient temperatures. The AMK fuel reduced the performance of some fuel subsystems but tolerated the presence of water.

In the Douglas tests, boost pump performance with AMK was below that with Jet A. There was some AMK degradation due to the boost pump, but this decreased as the flow rate through the boost pump increased. However, Douglas reported, even at low flow rates (high degradation), AMK retained good antimisting characteristics. The test results also showed that jet transfer and scavenge pumps performed more poorly with AMK. The scavenge jet pump produced unintentional degradation of virgin AMK, and because of the current DC-10 fuel system design, caused mixing of highly degraded fuel with virgin AMK. Minor changes in the design of the fuel system could minimize the mixing of the fuel, and use of a larger jet pump could make up for performance losses. Moreover, AMK's ability to hold large amounts of water could eliminate the need for the continuous scavenge system in the DC-10.

The lower performance of the boost pumps on AMK could mean that some high flow rate requirements such as those needed for dumping fuel or for feeding two engines from one pump might not be met.

The makeup flow from the boost pump, while highly degraded, was acceptable for initiating flow of AMK through the gravity transfer valve in the Douglas test without problems and with minimal degradation (reference 28). However, the rate of gravity flow was about 25 percent lower with AMK than with Jet A and would necessitate greater use of the jet pump transfer system. Actuation times for the float switches and float valves were the same with AMK and Jet A.

Douglas also ran an engine feed system test to determine the flow characteristics of the system during sea level and altitude operations using pressure feed and suction feed. In the pressure feed performance test, boost pump performance decreased with AMK, and the greatest degradation occurred at the low flow rate condition.

The system met flow and pressure requirements to the maximum certified altitude for the DC-10 and KC-10 (42,000 feet) with tank boost pumps operating. In the suction feed climb test, the engine pump cavitated at 31,000 feet altitude with AMK but delivered the required flow.

Douglas simulated fueling operations with batch-blended AMK on its DC-10 fill rig. Compared to Jet A, AMK had slower flow rates and longer system response times.

Fill valve actuation and shutoff were also slower with AMK. The shutoff delay produced larger overshoot volumes, and this would reduce useable fuel tank volume due to the need to maintain expansion space requirements. Unless modifications were made, this could lead to longer aircraft turnaround times.

In addition to the fill system and feed system tests, Douglas engineers took AMK through four flight cycles on the DC-10/KC-10 fuel system simulator to determine the fuel qualities at the fuel tank, engine fuel pump inlet and interstage for a typical flight (reference 28). Each cycle consisted of takeoff, climb, cruise, and descent and landing. The AMK samples from the fuel tank showed good fire protection characteristics. It retained most of its fire protection capability throughout the simulated mission. The DC-10 engine feed system, however, degraded the AMK to the point where antimisting properties were somewhat diminished. The engine fuel pump further degraded the fuel.

For the most part, Boeing's later work with inline-blended AMK fuel in a simulated aircraft fuel system confirmed Douglas's findings. Both programs demonstrated that the FM-9 AMK fuel retained its mist suppression properties when exposed to airframe fuel system operation at flight envelope and environmental extremes. The AMK fuel reduced the performance of some fuel subsystems — jet pump transfer, gravity transfer, suction feed and boost pump feed — below normally accepted levels under certain conditions. Such deficiencies, it is believed, could be remedied either by minor hardware changes or changes in fuel management procedures.

As part of its evaluation of AMK's compatibility with aircraft fuel systems, the FAA had Simmonds Precision Products conduct a literature search on commercial aircraft and helicopter fuel system designs (reference 54). The study focused on those components considered the most likely to encounter problems with AMK. The study also focused on polymer degradation and system operational safety. Simmonds concluded that further study of jet ejector pumps was warranted due to their extensive use in aircraft fuel systems and to their anticipated poor performance with undegraded AMK.

The company did not consider unintentional degradation of AMK by boost pumps to be a problem. Nor should the coarse screen filters used in most aircraft fuel systems prove to be a problem. But the fine, micron size filters used in auxiliary power units (APU's) and in some aircraft fuel systems would require additional study under actual operating conditions. Simmonds also concluded that APU's should be tested with degraders to insure that they can perform satisfactorily with AMK. Heat exchangers which transfer heat to static or near static AMK should not experience performance losses, said the company; but jet engine fuel nozzles would have to be redesigned to produce better spray patterns for more efficient combustion of undegraded AMK.

ENGINE COMPATIBILITY.

As part of the United States effort, Pratt & Whitney Aircraft conducted a 2-year technical assessment of the use of AMK in the commercial JT8D turbofan engine fuel system. The tests were conducted with batch-blended FM-9 AMK (references 12 and 13). The Royal Aircraft Establishment sponsored similar studies in the United Kingdom with Lucas Aerospace Ltd. Lucas evaluated the performance of an annular combustor from the Rolls-Royce high bypass ratio RB 211 engine and three different fuel injectors with batch-blended FM-9 AMK (references 49 and 65). Later, additional data on engine performance with inline-blended FM-9 AMK were provided by the ground and flight tests of the CV-880 and B-720 CID aircraft.

In general, both PWA and Lucas found that AMK had to be highly degraded prior to combustion in order to achieve maximum operating efficiencies and minimum carbon monoxide and unburned hydrocarbon emissions. Neither company uncovered any unsolvable problem, but both stressed the need for endurance testing (750-1,000 hours) to determine the long term effects, if any, of AMK on critical engine component performance and reliability.

The sensitivity of combustion performance to the degradation level of AMK was particularly evident at idle conditions in the Lucas tests (figure 12). For these tests, Lucas used an 80 degree -sector of an RB 211 annular combustor. With highly degraded AMK (FR = 1.2), combustion efficiency at idle dropped to 97.33 percent from 98.10 percent with Jet A. With less highly degraded AMK (FR = 2.9), combustion efficiencies dropped below 90 percent. At cruise conditions, Lucas obtained the same combustion efficiencies (99.97 percent) for highly degraded AMK (FR = 1.2) and Jet A. With AMK having a FR = 2.2, combustion efficiency at cruise dropped to 99.93 percent. At these same conditions, there was no apparent change in the thermal gradient patterns at the combustor exit (figure 13).

The minor patternator variations produced by the standard JT8D injector with partially degraded AMK (FR = 3), PWA reported in reference 12, indicated that existing fuel nozzles would be adequate with antimisting fuels, if improved degradation methods were made available (figure 14).

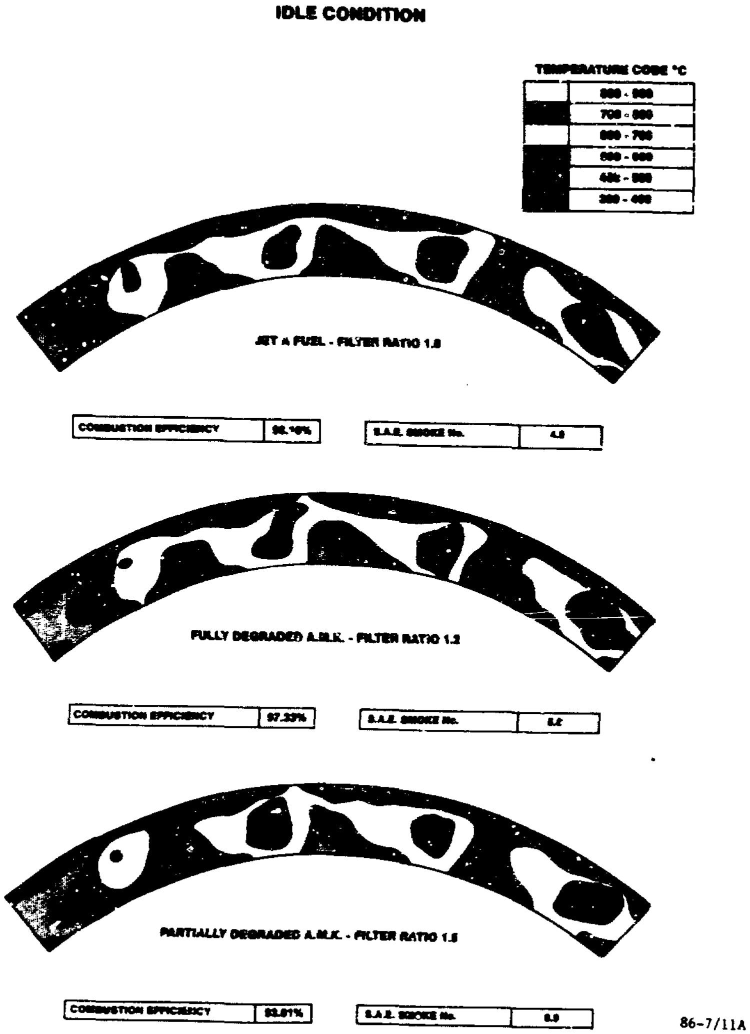
Lucas obtained similar results from its evaluation of fuel injectors with AMK (reference 65). The company tested a Spey duplex injector, an RB 211 airspray injector and a Lucas fan spray injector with AMK degraded to three different (unspecified) levels at fuel flow rates corresponding to ignition, ground idle, and full load. AMK produced larger droplets and coarser spray than Jet A. Only the fan spray injector produced atomization adequate for proper combustion, Lucas noted, and further deterioration in droplet size could be expected at low operating temperatures. Combustion tests at the relevant conditions are needed to determine the level of degradation required for trouble free combustion, according to Lucas.

Both the CV-880 flight test aircraft and the B-720 CID aircraft provided valuable data on engine performance with inline-blended and degraded AMK (FR = 1.2-2.0). In addition to flying successfully with AMK, these aircraft demonstrated that jet engines can be started on degraded AMK and relighted on it at altitudes between 10,000 feet and 30,000 feet at Mach 0.5-0.6.

AMK FLIGHT TESTS.

The first aircraft to fly with an engine operating on FM-9 AMK was the Convair 880 flight test vehicle with the General Electric prototype flight degrader (reference 56). The centrifugal pump-degrader was installed on the No. 3 engine which was fueled with AMK from the No. 3 wing tank. The aircraft's other three engines operated on Jet A. The No. 2 engine was instrumented to serve as the reference engine for the No. 3 engine.

Because of time constraints, GE used existing hardware as the foundation for the prototype degrader, namely: the augmentor centrifugal pump from its F101 military engine and an auxiliary power unit air turbine motor from the C-5A aircraft. A throttling valve from GE's F404 engine fuel system was used to reduce the fuel pressure to levels acceptable for the CV-880 main engine fuel pump. Excess fuel was recirculated to the degrader inlet through a heat exchanger (figure 15).



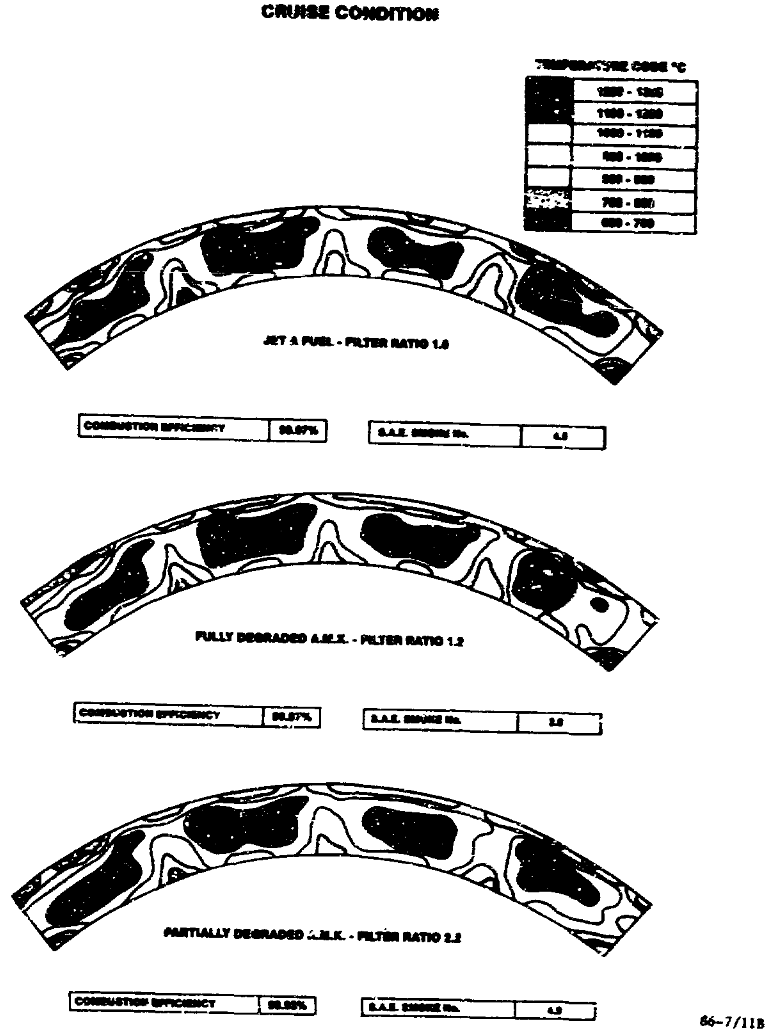


FIGURE 12. RB 211 COMBUSTOR SEGMENT TEMPERATURE PATTERN FACTORS

Temperature pattern factors from an RB 21 80-degree combustor sector at idle (left) and cruise (right) show the relationshiop between AMK degradation level, combustion efficiency, and temperature distribution.

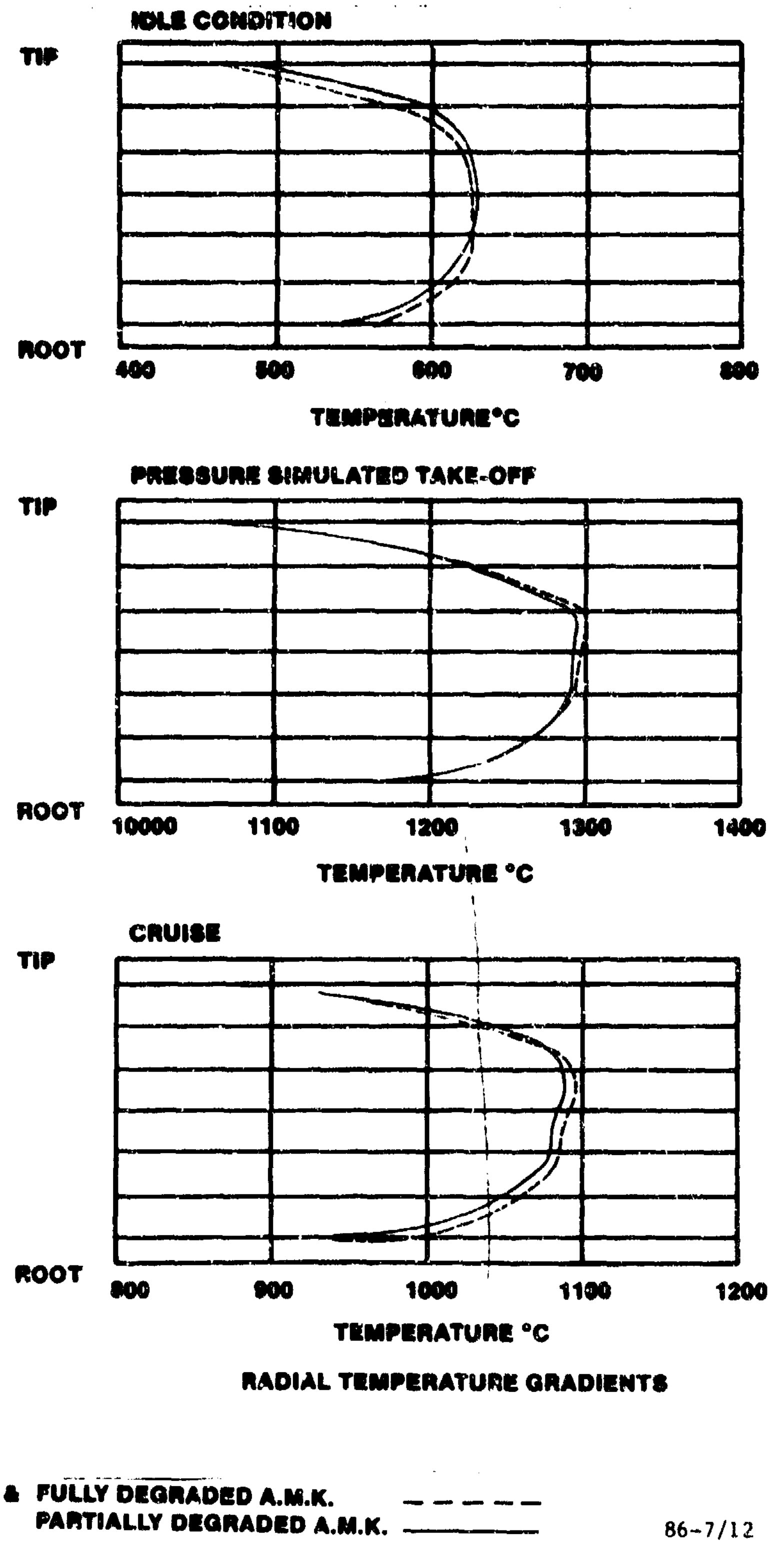


FIGURE 13. RB 211 COMBUSTOR SEGMENT RADIAL TEMPERATURE GRADIENTS
Tests run by Lucas Aerospace on an 80-degree segment of a RB 211 combustor with Jet A, partially degraded AMK and fully degraded AMK show insignificant differences in radial temperature gradients of the three fuels at idle, cruise and takeoff conditions.

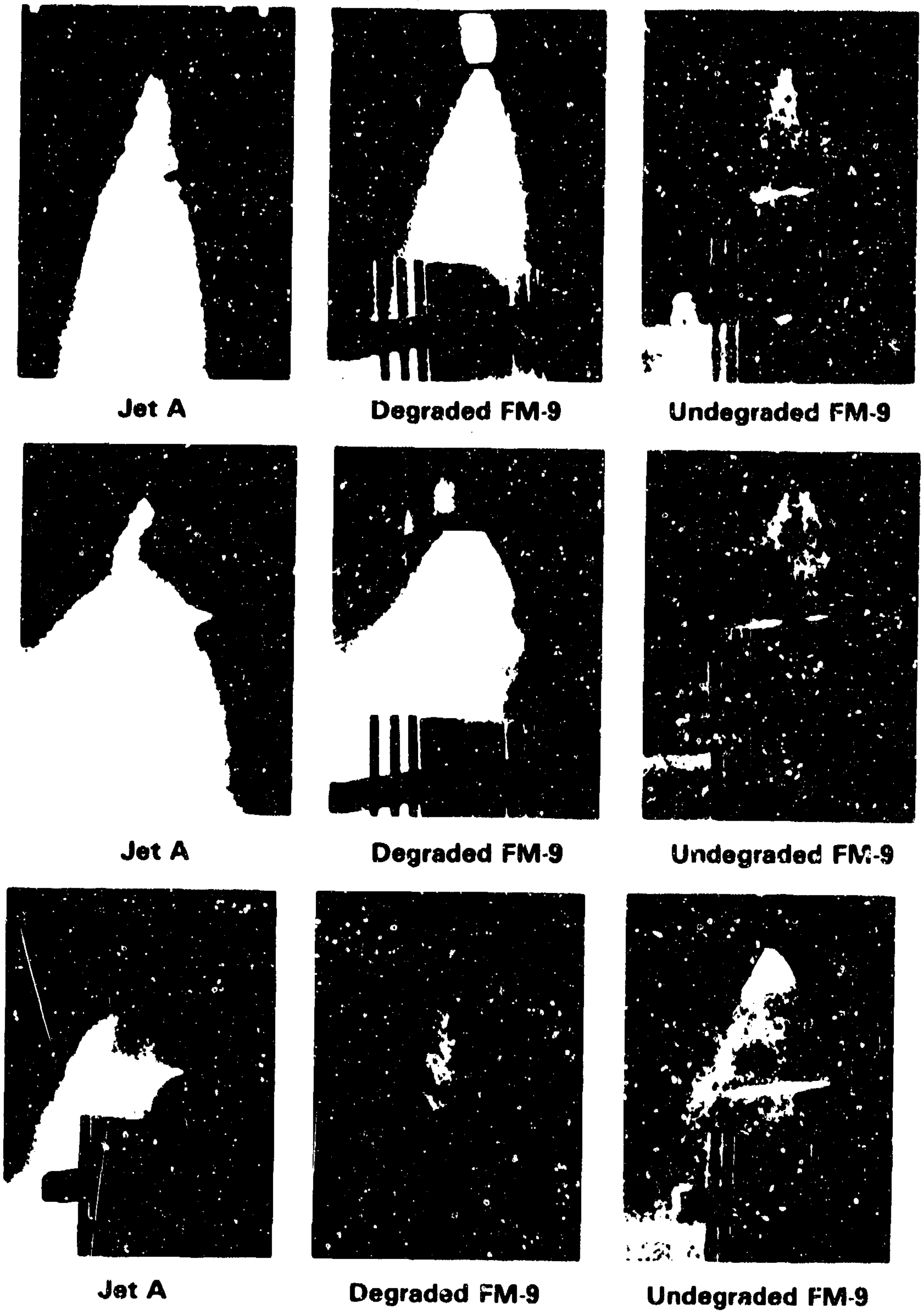


FIGURE 14. FUEL NOZZLE SPRAY PATTERNS WITH AMK AND JET A
Injector spray tests conducted by Pratt & Whitney with three different nozzles using Jet A and AMK showed AMK would have to be highly degraed to approach the atomization level of Jet A. Top row shows spray patterns obtained with a JT8D bill-of-material nozzle at cruise conditions. Middle row shows spray patterns produced by JT8D low emission nozzle at cruise conditions. Spray patterns obtained with an air-boost nozzle at cruise conditions are shown in the bottom row.

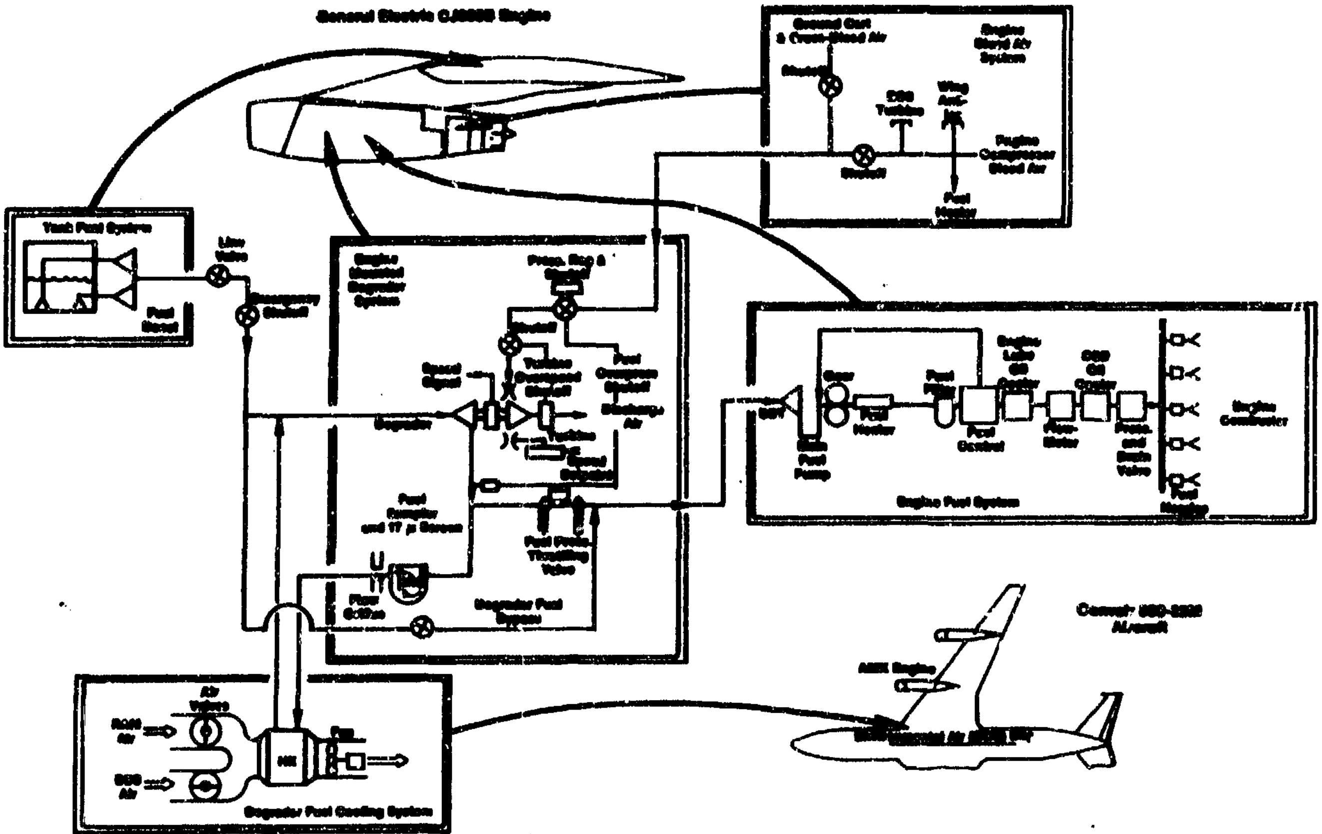


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FIGURE 15. FUEL FLOW SCHEMATIC FOR CV-880 DEGRADER
Drawing shows the fuel flow arrangement for the prototype degrader installed on the No.3 engine of the CV-880 flight test aircraft.

The same basic prototype degrader was installed on all four engines of the B-720 CID aircraft (figure 16). Hardware selection and installation locations were driven by expediency, not by considered design. In the CV-880, the air-fuel heat exchanger was located in the environmental control system bay; in the B-720, in underwing pods. The degrader in the CV-880 was located on the bottom of the engine; in the B-720, they were installed on the tops of the engines. In production systems, the degrader could be integrated with the main engine fuel pump to reduce weight and power requirements. Except for additional instrumentation, no modifications were made to the engine fuel systems downstream of the degraders.

General Electric installed the degrader on the No. 3 engine of the CV-880 in January 1984. On February 10, the plane took off from Miami using Jet A in all four engines. At 10,000 feet, the No. 3 engine was switched to AMK and operated for 77 minutes before being switched back to Jet A for the landing. The aircraft accumulated 30 hours of flight time and 15 hours of ground test time on AMK.

The objectives of the CV-880 flight test program were to use a representative commercial aircraft to determine the effects of AMK on aircraft fuel system performance, the effect of fuel systems and flight environment on the quality of AMK, and the installation and operational requirements for a prototype flight degrader (references 56 and 66). Although the CV-880 is no longer used by U.S. airlines, the airframe and engine fuel systems are considered representative of current aircraft systems.

The program was successful, providing the technical data and the design refinements necessary for the installation and operation of the four prototype degraders used in the B-720 CID aircraft (references 67 and 68). Specifically, the CV-880 engine ground runs and 14 flight tests demonstrated the following:

o Successful degrader operation on AMK for 45 hours with no major hardware or design problems.

o Flight and ground tests of engine and degrader run successfully over the range of fuel temperatures from 0° F to 90° F.

o Acceptable ground starting at 50° F to 90° F fuel temperatures.

o Successful altitude relight with AMK at 10,000 feet to 30,000 feet — same as Jet A.

o Engine acceleration/deceleration on AMK at 10,000 feet to 40,000 feet -- same as Jet A

o Fuel samples from degrader discharge line showed AMK to be highly degraded.

o Fuel sample from No. 3 tank indicated high mist suppression potential maintained throughout flight.

o Freshly inline-blended AMK successfully degraded within 15 minutes of blending.

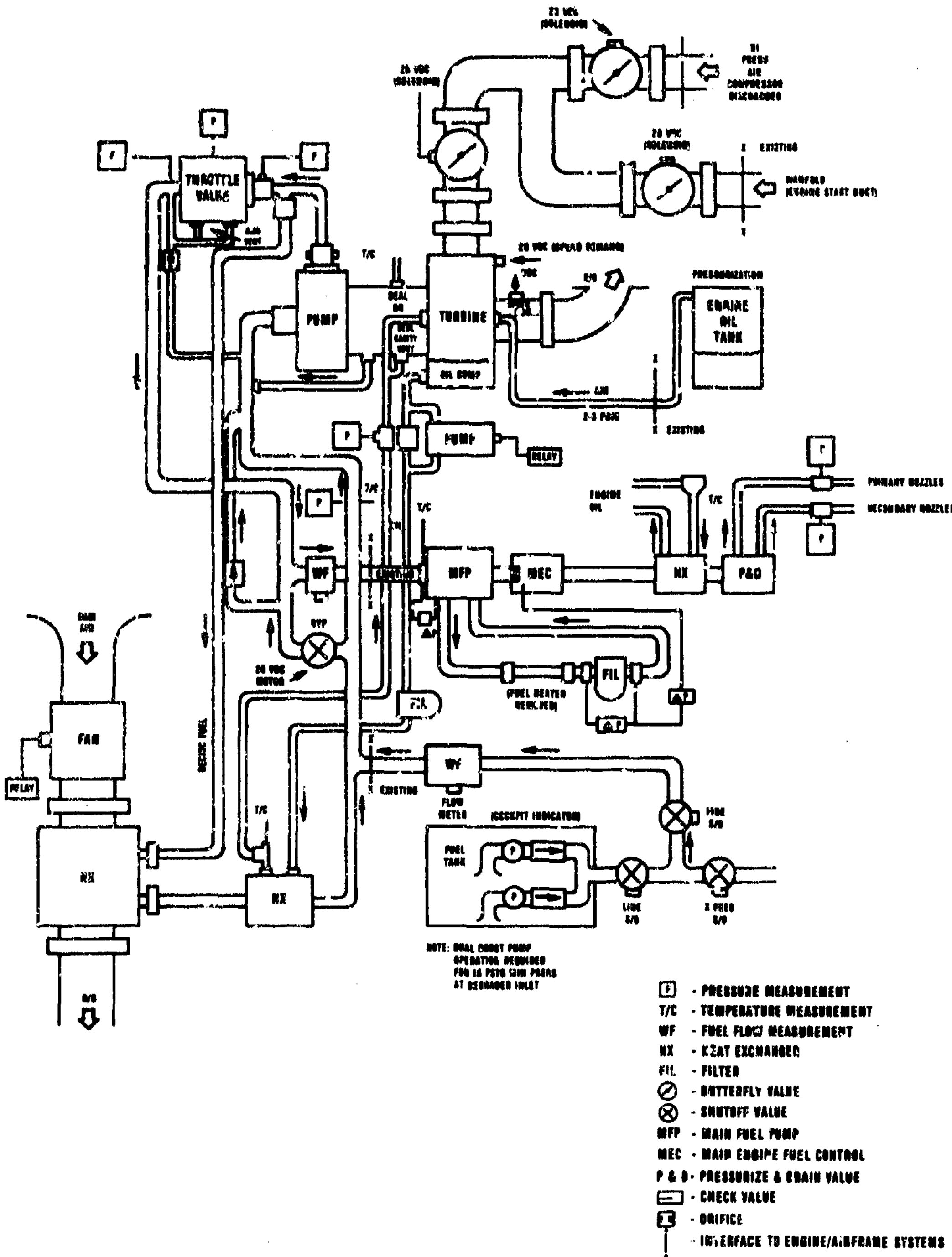

FIGURE 16. FUEL FLOW SCHEMATIC FOR B-720 DEGRADER
Drawing shows the fuel system installation and instrumentation for the prototype AMK degraders installed on the four engines of the B-720 CID aircraft.

At the start of the CV-880 AMK program, an insoluble gel formed on the engine and degrader fuel system filters and screens in several ground and flight tests. Because the gel problem did not occur during the final 26 hours of the program, the degrader was absolved of any blame. The problem also had occurred earlier in RAE tests of AMK in a Spey engine and in FAA Technical Center tests of a JT3C engine. Dirt and contaminants, which may have accumulated in the system prior to the introduction of AMK, are considered the probable cause of the gel because FM-9 AMK is highly detergent. But the problem needs more study to provide a definitive explanation of these gel occurrences.

In the course of the CV-880 AMK program, the degrader was intentionally shut down inflight while operating on AMK. There was a step increase in the differential pressures across the engine fuel filters, but the engine continued to operate normally on undegraded AMK (references 66 and 69). After the degrader was restarted, the pressure returned to normal with the engine continuing to operate on AMK. Work by SwRI and the FAA had shown that when the flow rate of AMK exceeds its critical velocity through a filter, it will form a shear induced, soluble gel on the downstream side of the filter. When the flow rate is reduced — or the level of degradation increased — the gel will dissolve, and flow will resume unrestricted.

By February 1984, GE had installed the four prototype flight degraders on the B-720 aircraft that was to be used in the FAA/NASA Full-Scale Transport Controlled Impact Demonstration Program (reference 70). Each degrader-engine system was first qualified on Jet A before it was ground and flight tested on AMK. The center wing tank, override boost pump and the crossfeed manifold system were used exclusively to deliver AMK to each of the four degrader-engine systems during the manned flight tests.

The B-720 made its first flight with the No. 3 engine operating on AMK in August 1984, and the following month flew with all four engines operating on AMK. The manned flight tests of the B-720, prior to CID, uncovered only minor problems in the areas of mechanical installation, instrumentation, degrader control and in operational procedures (reference 69).

During a go-around climbout, a degrader inadvertently shutdown while operating on AMK. The engine continued to operate normally for about one minute before being switched to Jet A. The crew reported that it was unaware of any operational differences during this period. The flight engineer's degrader control panel and the ground control room readouts gave the only indications of degrader shutdown. They showed the characteristic pressure rise across the fuel filters which dropped back to normal immediately after the switchover to Jet A. Post-flight inspection of the filters showed no evidence of residual, shear induced gel.

Engine flight performance with AMK was comparable to that with Jet A (reference 69). The AMK fuel samples taken from the boost pump inlet during ground runs showed high degradation levels at idle and at intermediate and high power levels. The samples taken from the wing tank prior to and after two manned flights indicated no significant reductions in fuel quality. Prior to the final CID flight, the B-720 degraders had accumulated 27 hours of operation on Jet A and 11 hours on AMK.

CONTROLLED IMPACT DEMONSTRATION.

With regard to AMK, the Full-Scale Transport Controlled Impact Demonstration Program (CID) was designed to demonstrate that a jet transport could operate successfully solely on AMK and that AMK could prevent ignition of an airborne fuel mist or suppress the growth and propagation of an airborne fireball. On its final flight, the B-720 CID aircraft was to be remotely flown and crashed into a prepared impact site under conditions that would produce an impact-survivable accident with postcrash fire when fueled with normal Jet A — the type of accident that might be expected during an approach, landing, missed approach, or aborted takeoff.

After detailed studies of past accidents and related research at the Technical Center, the FAA developed a severe impact scenario that called for the aircraft to be on a 3.3° to 4.0° glide path in a 1° nose-up attitude on final approach. The aircraft was to have a nominal sink rate of 17 feet/second with essentially no roll or yaw and was to impact with a longitudinal velocity of 145-155 knots with wheels up to provide severe fuselage impact forces. The prepared stone bed impact site (figure 17) contained heavy steel structures designed to rip open the wing fuel tanks to insure fuel spills of 20-100 gallons/second (figure 18). The fuel would be exposed to a variety of ignition sources during slideout: friction from the stone bed, engines separated from the wing, the aircraft electrical system, operating approach lights installed at the site, and two jet fueled flame generators in the aircraft tailcone to simulate ignition by aft-mounted engines.

On November 29, 1984, FAA personnel fueled the aircraft with 11,325 gallons of inline blended AMK. Analysis of fuel samples taken from each tank showed that high quality AMK developed within the first hour after completing the blend (reference 69). On December 1, 1984, the engines were started on degraded AMK and operated normally throughout the 40 minutes of preflight checks. At 9:13 A.M., the CID aircraft took off from Edwards AFB for its final flight. Engines and degraders responded normally to the fuel flow demands of the remotely located NASA crew throughout the nine minute flight.

Despite many practice tests, the CID mission proved to be a high workload task for the NASA pilot. Using the onboard autopilot as his primary control and a television camera in the nose of the aircraft for his eyes, the pilot had to integrate information from many sources to meet the tight impact constraints (reference 68). Consequently, he was unable to meet all impact requirements, and the impact deviated from the planned scenario.

Contact was 410 feet short of the target with the aircraft in a 2-degree nose-down attitude in a 13-degree yaw to the left and rolled left 13 degrees. During slideout, the aircraft continued to yaw to the left and came into contact with the first of the steel wing openers at a yaw angle of 38 degrees (reference 69).

The aircraft's left outboard (No. 1) engine made the initial contact with the ground. The No. 1 and No. 2 engines spooled down to cutoff immediately after the left wing and fuselage contacted the ground. Both engines separated at the pylon during the next two seconds, prior to reaching the wing openers. The aircraft slid 500 feet before reaching the wing openers, and its speed had decreased to 122 knots from the 152 knots at initial impact.

By the time the aircraft contacted the first wing opener, its right wing was almost perpendicular to the center line of the impact zone, and both right wing engines

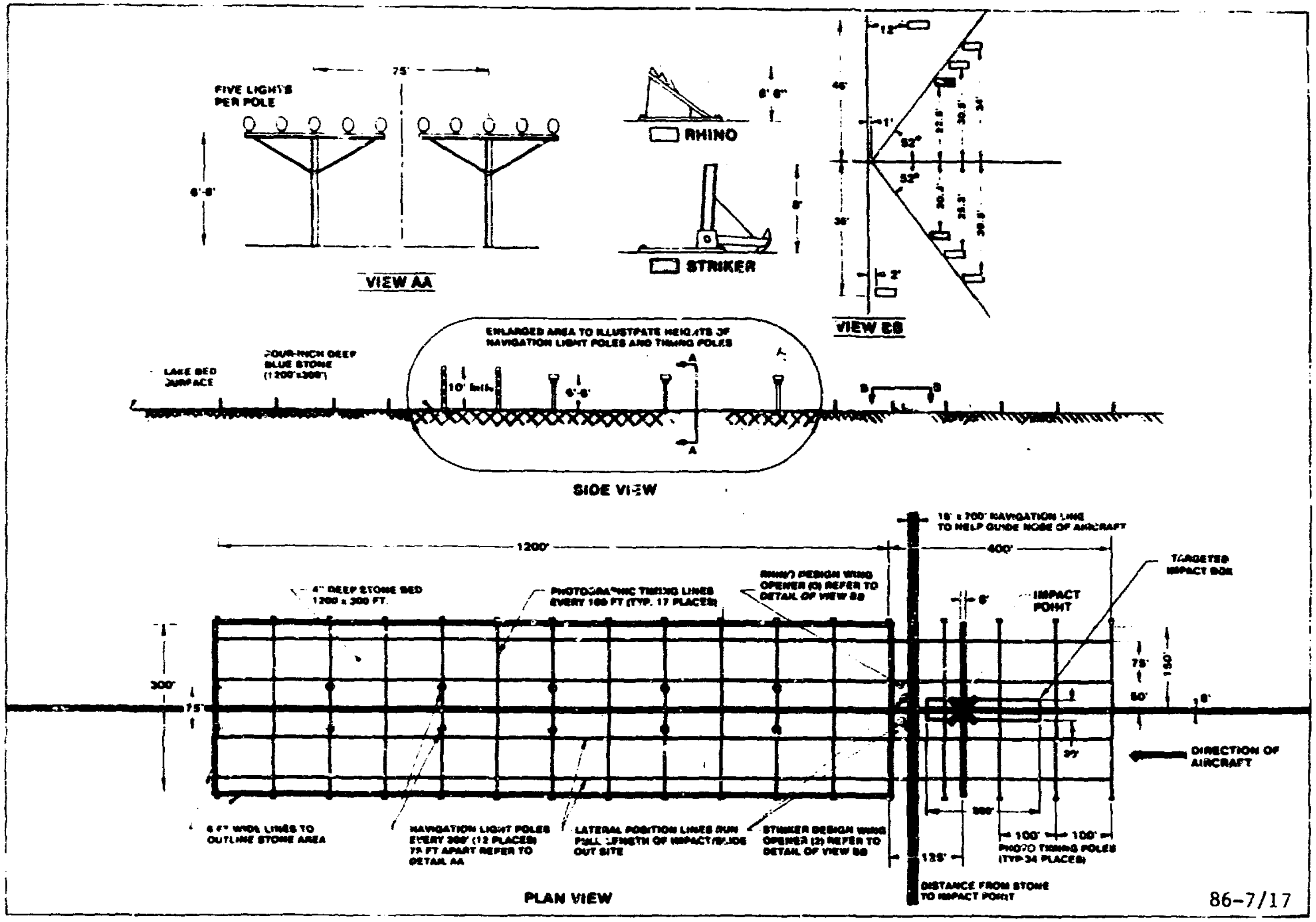

FIGURE 17. CID IMPACT SITE
Side and overhead views of the prepared CID impact site show stone bed and approach lights designed to serve as ignition sources and locations of the wing openers.

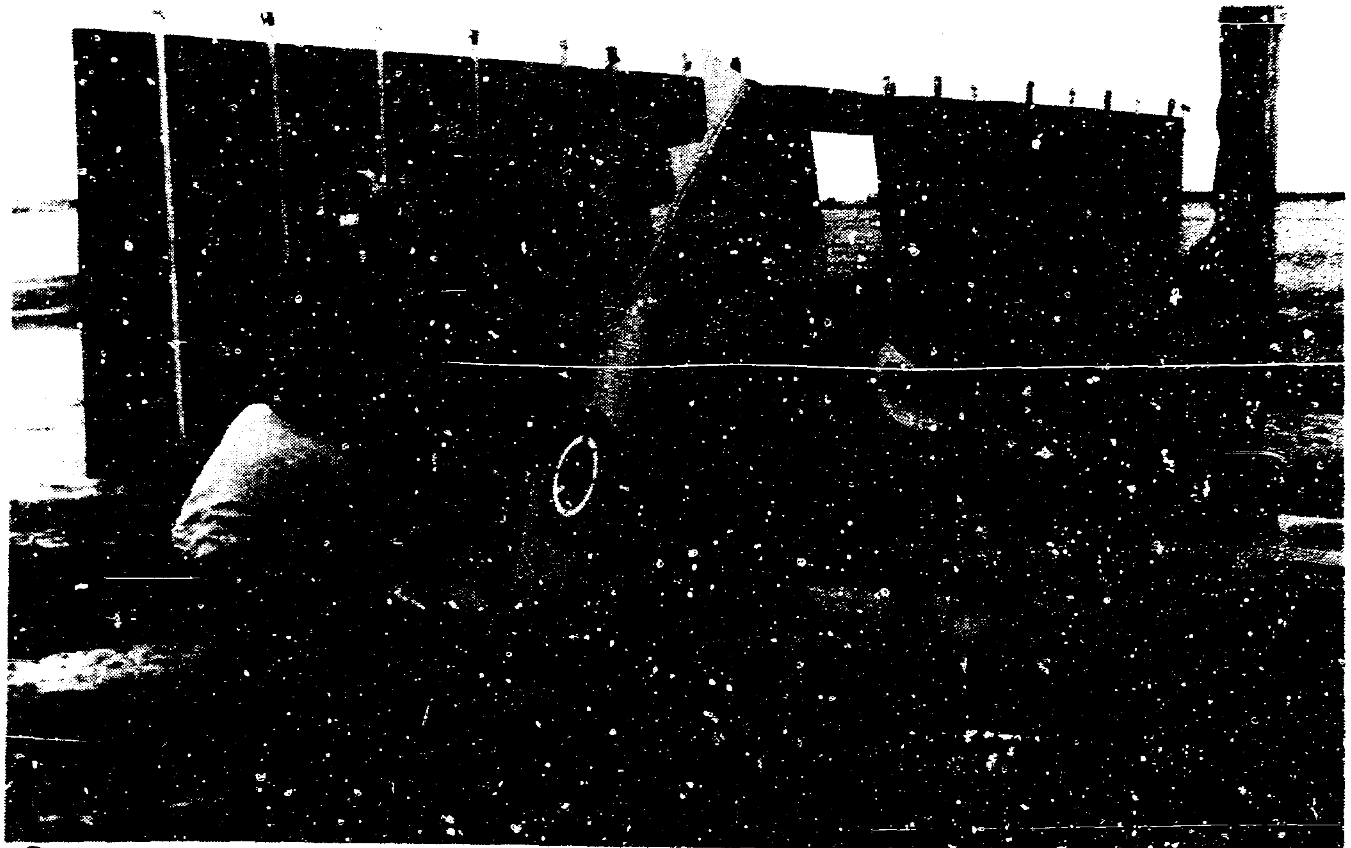

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FIGURE 18. CID WING OPENERS
Steel structures installed in the CID impact
site were designed to rip open wing fuel tanks.

(No's. 3 and 4) were still operating. The first of the wing openers to strike the aircraft entered the side of the No. 3 engine nacelle and continued through the engine, stopping compressor rotation within one revolution (figure 19). As the opener buried itself in the No. 3 engine, its base broke loose from the anchors and rotated upwards, cutting into the underside of the wing. Simultaneously, a second wing opener ripped through the underside of the wing just inboard of the damaged No. 3 engine, causing sufficient damage to separate the right wing.

The right wing separated just inside the inboard engine and rotated upwards, releasing most of the fuel (2,150 gallons) from the inboard main tank. The right inboard engine, although broken in two, remained attached to the wing stub until the final 100 feet of aircraft slideout (figure 20). Because of the 38-degree left yaw, three wing openers on the right side severely damaged the fuselage, opening holes through which fuel from the severed wing entered the cargo area. Also, during initial impact with the ground, the right forward cargo door opened, allowing additional fuel to enter the cargo area.

Ignition occurred on the inboard side of the No. 3 engine within 0.14 seconds after initial impact with the wing opener (reference 69). Unlike that typically produced by AMK, the initial ignition probably involved lubricating oil, hydraulic fluid and degraded AMK from the broken No. 3 engine. Moreover, considerable turbulence was being generated by the sidewards slide of the fuselage and the release of large amounts of fuel from the severed wing which was rotating in front of the fuselage. This also created an area of intense recirculation between the fuselage and the severely damaged No. 3 engine. AMK fuel spilled into this region and was repeatedly sheared (degraded) and exposed to heat from the burning combustible fluids and the hot engine surfaces. The shear and extended residence time caused the AMK fuel to vaporize and burn.

Prior to viewing the detailed photographic evidence, most observers' initial impression was that the AMK had failed to suppress the mist fireball and, in fact, had initiated a large pool fire (reference 71). But a careful review of the film revealed that the fire was not the result of misted, undegraded AMK fuel but rather the combination of burning hydraulic fluid, lubricating oil, and degraded AMK fuel. The airborne fire that engulfed the fuselage went out within eight seconds and left the fuselage with only minor fire damage. The film also showed that there was no large pool fire when the aircraft came to rest. The fire that eventually destroyed the aircraft was caused by burning fuel that had entered the openings in the lower fuselage as a result of the aircraft's high yaw angle.

Without the high yaw angle, any flame from the wing area would have blown aft without impinging the fuselage (reference 69). The No. 3 engine would most likely have separated from the wing on impact with a wing opener or the ground. If the CID had gone as planned, the results would have been significantly different. Any fire that developed would have been limited to areas aft of the aircraft, attached to a separated engine or in the form of a slow developing ground fire.

If the fuel had been Jet A instead of AMK, even a minor ignition source would have led to a devastating fire. The degree of yaw would have been inconsequential. The airborne fire would have been characterized by much faster flame growth and higher heat transfer rates, and the fire would have propagated rapidly to the fuel release points and remained attached to the aircraft after slideout.

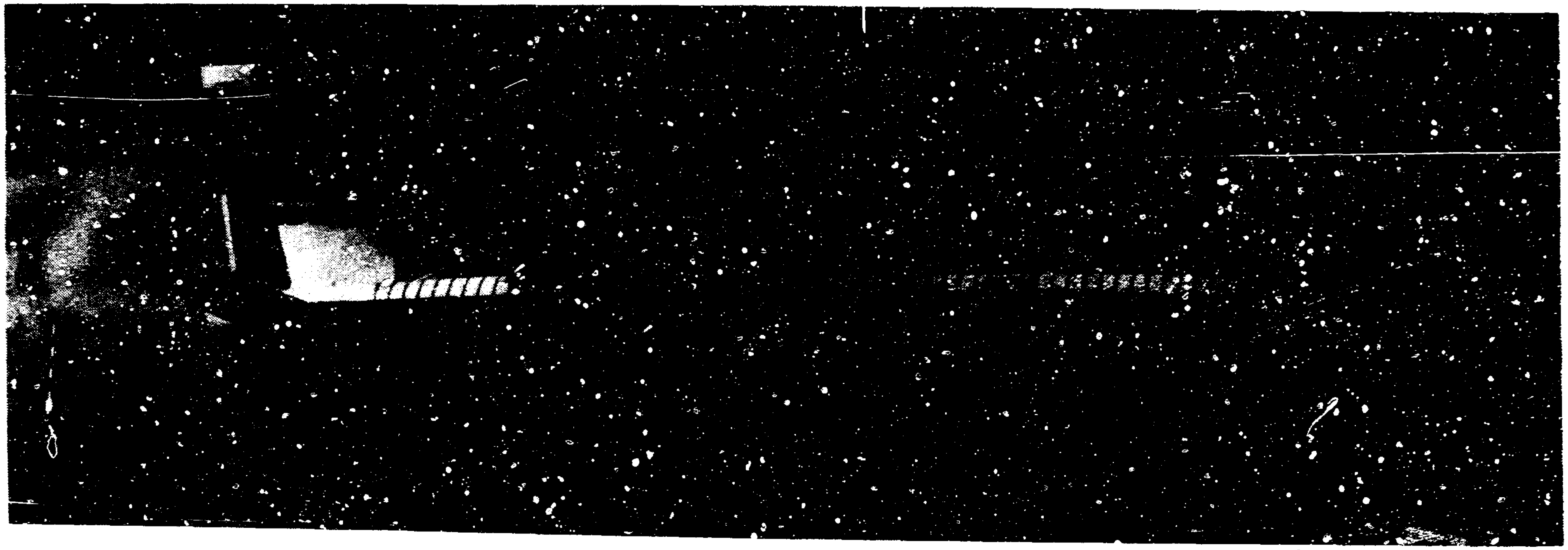

FIGURE 19. B-720 IMPACT WITH WING OPENER
First steel wing opener sliced through the No. 3 engine at the seventh compressor stage. The engine stopped within one revolution, and ignition occurred on the inboard side of the engine.

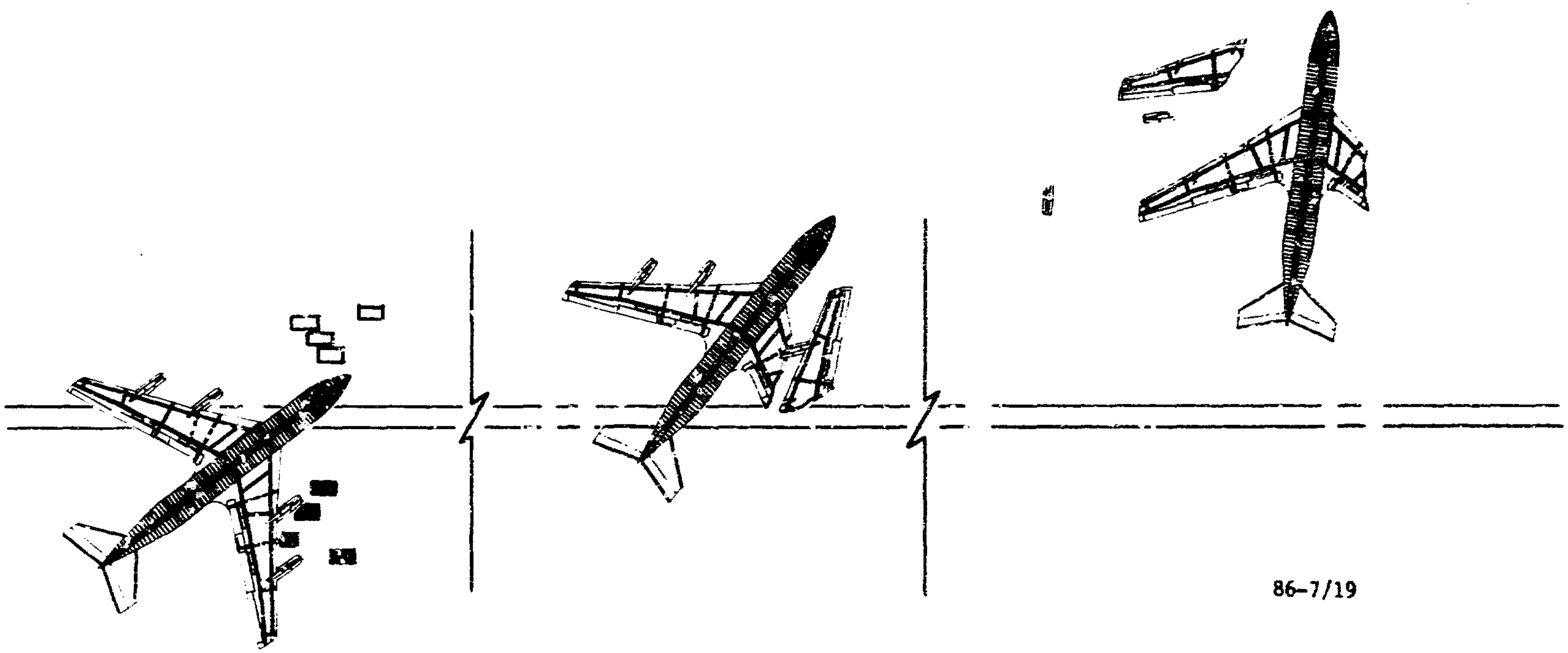

FIGURE 20. DRAWINGS OF IMPACT SEQUENCE
The right wing of the CID aircraft separated just inside the No. 3 engine after being struck by a wing opener and rotated upwards, releasing most of the fuel from the right inboard main tank.

POST-CID STUDIES.

Following the CID, FAA and its contractors undertook studies to determine the reasons for the large ignition and continued burning of AMK and to learn why the severe flames that engulfed the fuselage for eight seconds produced only minimal fire damage (references 66 and 72).

In a series of tests at the Technical Center, FAA engineers and technicians used the wing-fuel spillage facility to duplicate most of the critical CID parameters. They mounted a fully cowled, 3,000-pound thrust class PWA J60 turbojet engine under the airfoil section at an angle of 38° to the airflow (figure 21). With the engine at 90 percent power and the airflow set at 125 knots, they released AMK fuel into the airflow at the rate of 300-400 gallons/second.

In one test, fuel inadvertently entered the engine inlet causing a surge. Although not a factor in CID, the surge ignited the fuel, and a continuous fire immediately established itself in the sheltered path downstream of the engine. Fuel continuing to pour out the airfoil orifice showed the coarse spray characteristic of AMK, and there was no upstream propagation of the fire. This illustrated what probably occurred in the CID following the initial ignition. The turbulence and recirculation in the area sheltered by the engine and pylon generated sufficient shear force to degrade the AMK, and recirculation provided sufficient residence time for the fuel to vaporize and burn after being exposed to a severe ignition source — in this test, the engine surge.

In subsequent tests, with the engine oriented inline with the airflow (as was planned in CID), a new phenomenon occurred (figure 22). The AMK entrained by the engine exhaust produced an extremely fine fuel mist. The high velocity exhaust generated severe shearing forces that degraded the AMK. A spark gap ignitor placed in the plane of the exhaust did not ignite the AMK mist but a small, open flame did. This phenomenon did not occur in CID because the No.3 engine was stopped within one revolution, before the fuel could become entrained.

From another series of post-CID tests conducted by JPL, there is evidence that AMK will afford a significant measure of fire protection in crash situations after the aircraft comes to rest, where fuel is released vertically from ruptured tanks and not subjected to the normal aerodynamic shearing action that induces antimisting characteristics (reference 73). JPL researchers dropped 5-gallon test samples of Jet A and AMK onto impact sites containing pools of fuel (Jet A or AMK) and propane torch ignition sources. The fuel, shielded from aerodynamic forces, was dropped from heights ranging from 6 to 30 feet.

Preliminary data showed that the impact of a 5-gallon sample of Jet A dropped from a height of 7 to 8 feet generated sufficient fine mist to trigger a major ground pool fire. AMK dropped under identical test conditions and from heights up to 30 feet generated no mist and actually suppressed ignition of splashed fuel and any accompanying pool fires.

From other post-CID tests, there are indications that the slower propagation rates of burning AMK and the breakup of AMK into coarse droplets resulted in a lower flame temperature and slower heat transfer than would have occurred with Jet A. This would account for the relatively good condition of the fuselage after the flames lifted. But additional work is needed to define more precisely the ignition

FIGURE 21. POST-CID TEST ON WING-FUEL SPILLAGE FCILITY
To learn more about what happened at CID, FAA ran a post-impact test at the Technical Center using a small jet engine angled 38 degrees to the airflow from its wing-fuel spillage facility.

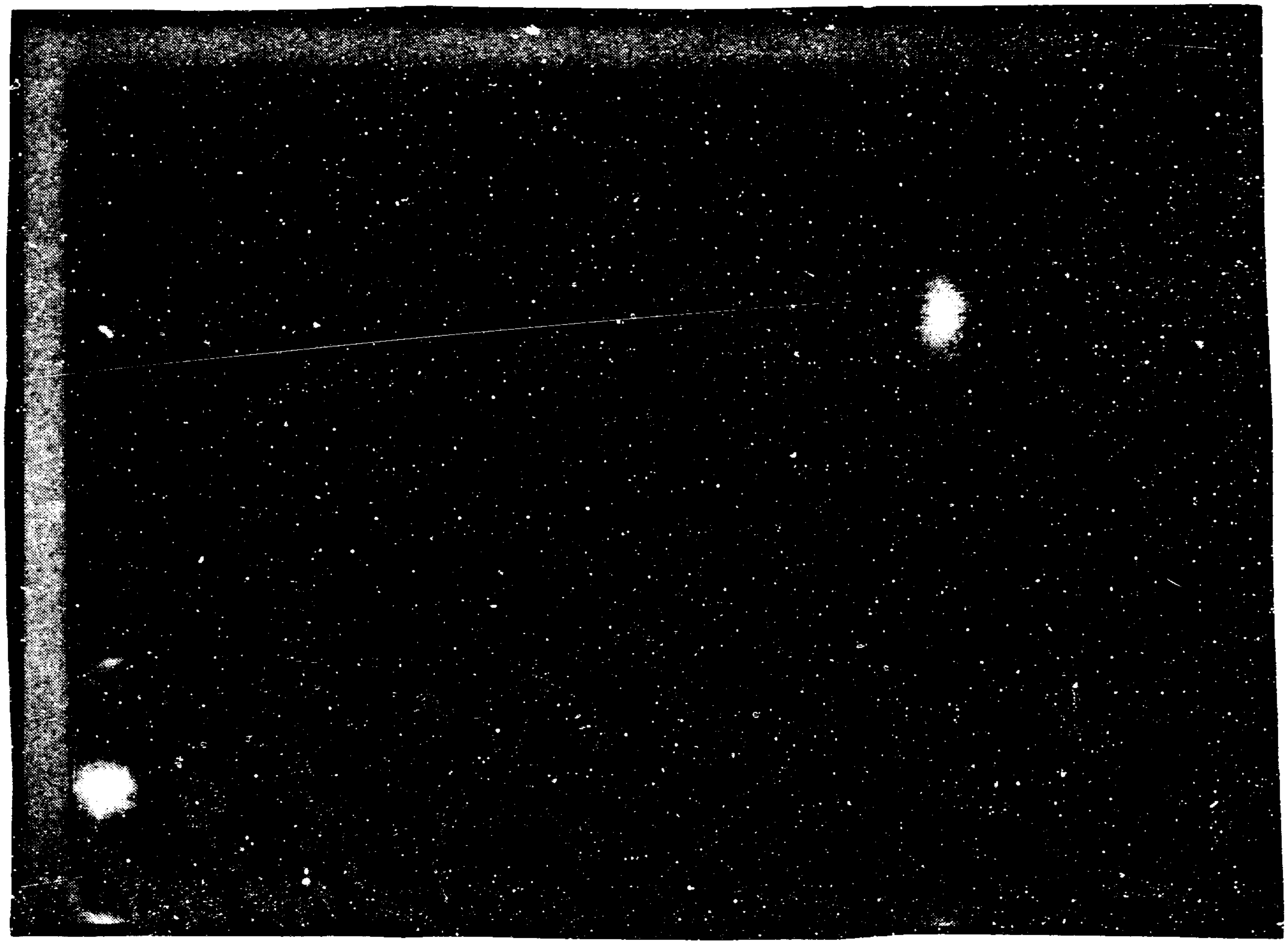

FIGURE 22. FUEL ENTRAINMENT IN ENGINE EXHAUST

In one of the post-impact tests run with the wing-fuel spillage facility and an engine aligned with the airflow, FAA encountered the hertofore unseen phenomena of fuel being entrained by the engine exhaust.

envelope and burning characteristics of AMK under these unique conditions. Additional work is also needed on engine exhaust entrainment as a potential ignition factor for AMK.

Results of such studies would more accurately define AMK's envelope of effectiveness and any aircraft modifications needed to enhance the postcrash fire protection provided by AMK fuel. They would also help in establishing the performance requirements for future AMK fuels.

AN UNCOMMON ACCIDENT.

While no experiment as complex as CID can be expected to perform exactly as planned, post-CID investigations indicated that CID was unique (reference 66). A detailed review of the National Transportation Safety Board (NTSB) data on over 700 accidents involving U.S. turbine-powered aircraft from 1964 through 1983 revealed no impact-survivable accident that had all the critical elements of CID, namely: post-crash fire; major wing-mounted engine damage without separation; large fuel release at the damaged engine; yaw greater than 30 degrees; and fuel ignition between 100 and 150 knots.

Moreover, using information from the NTSB data, engineers at the Technical Center estimated that AMK could have provided protection in at least 79 percent (34 out of 43) of the impact-survivable accidents with postcrash fires that occurred in this 20-year period (table 2). Approximately 23 percent of the accident reports provided insufficient data for any conclusion on the potential benefit of AMK. When reports were available, there were few or no details on location and size of the fuel release, source and location of ignition, or on the sequence of events during and immediately after slideout. Correction of these omissions in future accident reports could prove extremely helpful in future safety work on fuels.

TABLE 2. SUMMARY OF DOMESTIC POSTCRASH FIRE ACCIDENTS (1964 - 1983)

		Fatalities		
	Number	Impact	Fire	Unknown
Accidents With Sufficient Data	70	1230	348	600
Impact Non-Survivable	27	758	0	442
Impact Survivable	43	472	348	158
Impact Survivable and AMK Protection	34	472	346	156

COST CONSIDERATIONS.

On a strict economic basis, the use of FM-9 antimisting fuel in commercial aircraft is difficult to justify due to the present high level of air travel safety.

In its study of the economics of using AMK, which began in 1980, the Aerospace Corporation had to make several assumptions (reference 74). Some of these assumptions have proven optimistic; others, pessimistic. But the methodology and general conclusions still appear to be valid. Costs and benefits were calculated in 1981 dollars and computed at a 10 percent discount rate. The value assigned to a human

dollars and computed at a 10 percent discount rate. The value assigned to a human life was $500,000. The cost for jet fuel was calculated at $1/gal, and the additional cost for using the FM-9 additive was figured to be 6.9 cents/gal. The Aerospace analysis also assumed a 20-year (1987 through 2006) useful lifetime for the investment.

Other assumptions made in the study were: 135 worldwide fire-related fatalities a year during the 1970-80 decade that could have been prevented by the use of AMK; 1.45 aircraft/year that could have been salvaged had AMK been used; FM-9 would be added as a slurry by inline blending during aircraft fueling and at current fill rates; 0.9 percent more fuel would be required to compensate for the lower energy content of the AMK (0.4 percent) and the fuel consumed by the degrader (0.5 percent). A more realistic figure for the additional fuel required would have been 0.13 percent. Aerospace assumed that FM-9 AMK would have a slightly lower heating value than straight Jet A and that the engine would need 0.5 percent more fuel to drive the degrader. Work by SwRI indicated that the additional fuel needed to drive the degrader would be less than 0.1 percent to drive a 30 h.p. degrader.

In its cost-benefit analysis, Aerospace Corporation calculated that the costs of using FM-9 AMK would outweigh the potential benefits by a factor of approximately 30. The study also showed that the largest cost factor was the additive and that a reduction in additive cost would significantly reduce total cost. Aerospace analysts also determined that airline passengers who valued their lives at more than $500,000 would be willing to pay the additional 2.6 percent ($3.92) for AMK protection for an average, medium haul (1,400 miles) airline ticket (table 3). This additional amount, according to Aerospace, would cover the additional amortized and operating costs for the first year of using AMK. Subsequent annual costs would be slightly lower.

TABLE 3. AMK IMPACT ON DIRECT OPERATING COSTS (DOC)

Item	DC-10	B727-200
1987 DOC W/O AMK	3951	2185
($/Block-Hr)		
Impact of AMK		
($/Block-Hr)	211 (5.3%)	128 (5.9%)
(/Revenue Passenger Mile)	0.28 (2.6%)	0.45 (3.0%)
($/Trip)	3.92 (2.6%)	2.25 (3.0%)

Another FAA contractor, Trans Systems Corporation, developed a computer spread sheet program based on the Aerospace study (reference 75). This program can be used to determine the effects on the various costs and benefits of changing one or more of the variables such as fuel costs. Trans Systems used different costs and values than Aerospace in some cases and also made different assumptions. Like Aerospace, however, Trans Systems overestimated the need for additional fuel. Nevertheless, the computerized spread sheet is useful for calculating cost-benefit trade-offs of using AMK.

Later, in a second study for the FAA, Trans Systems used the computer spread sheet program to assess the projected economic impacts of implementing the use of antimisting kerosene in (1) the worldwide turbine-powered air carrier fleet, (2) U.S. turbine-powered commercial transport, and (3) U.S. turbine-powered commuter aircraft (reference 76). In all the scenarios it studied in this program, Trans Systems came up with very low benefit-to-cost ratios.

In another study for the FAA, B&M Technological Services, Inc., analyzed the economics of different plans for introducing AMK into commercial use in the United States (reference 77). B&M used life-cycle costing techniques to evaluate segmental introduction of AMK versus fleetwide introduction. It also identified the most promising candidate aircraft for early use of AMK. The company concluded that fleetwide introduction of AMK would produce the maximum safety benefits and the maximum cost impact. Segmental introduction would minimize cost impact and potential capacity restraints on aircraft and airports.

B&M used a dual classification system: Aircraft were classified according to the number of engines and by the type of service. The company identified narrow-body, twin turbofan aircraft as the most promising candidate for initial use of AMK. Use of AMK by this fleet segment would increase safety on a larger proportion of departures and revenue passenger enplanements in both domestic trunk and local service. Then, for minimum cost impact, would come 3-engine, wide-body aircraft and four-engine, wide-body aircraft. (Comparable data on four-engine, narrow-body aircraft were not available.) Use of AMK in twin-turboprop aircraft would have the lowest unit cost impact, according to B&M, but would not cover enough passengers to make a significant difference in safety.

CONCLUSIONS

The results of eight years of development and testing indicate that antimisting kerosene fuel would provide a very high degree of protection against postcrash fuel mist fires in impact survivable accidents. This protection would be available a few minutes after fueling and would cover most conditions encountered during takeoffs. At the end of a typical commercial flight cycle, the remaining AMK would provide essentially the same degree of protection as on takeoff.

With modified airport fuel handling procedures, inline blending of AMK at the aircraft fueling point appears to be feasible and practical for routine commercial operations. Development of production blenders and efficient, flightweight degraders should present no problems. Airport fueling standards will have to be improved to prevent the accidental introduction of bulk water which could cause severe precipitation problems in fuel systems containing FM-9 AMK. Environmentally introduced water through condensation and coalescence during operational use would not be a problem.

AMK's heat transfer, friction and viscoelastic rheological properties have been explained and quantified beyond the point needed for routine operational use. Laboratory tests are now available for characterizing the fuel's antimisting, filtration and flammability properties and level of degradation. Real-time evaluation of fuel quality is possible and can be easily computerized for an operational system.

Although it could be improved with modified fuel nozzles, engine performance on degraded AMK is satisfactory, even in critical areas such as altitude relight. Degradation can be achieved without excessive power by making use of the degradation that occurs throughout the fuel system and then using a modified engine boost pump to complete the process. Using the basic principles already demonstrated in prototype units, manufacturers should be able to design practical, flightweight pump/degraders.

The lack of long-duration tests of aircraft fuel systems using AMK leaves some questions unanswered on system reliability and on the changes necessary for civil aircraft operation with antimisting fuel. Some of the following components may have to be modified or replaced on some aircraft: jet pumps used for critical fuel transfer, tank fill valves, engine system filters, engine boost pumps, and fuel flow meters. For efficient operation of the engine fuel control system, heat exchangers, combustors, and fuel nozzles, the AMK must be highly degraded. Component modifications and procedural changes needed for efficient and safe operation on AMK are technically feasible. Endurance testing would be required, of course, before AMK could be put into operational use. The AMK must be proven to be operationally as safe as current Jet A fuel.

The additional cost involved in using AMK (fuel additive cost plus aircraft and airport modification costs) is currently estimated at 4 to 7 cents/gallon or a 2 percent to 3 percent increase in the cost of an airline ticket. A computer program has been developed for determining the costs of introducing and using AMK and for weighing these costs against benefits. The data used in this program can be updated as needed.

Based on a detailed analysis of past accident data, the CID appears to be a unique event (reference 1). The unusual geometry and flow patterns are highly unlikely to occur in future accidents. However, the entrainment of spilled fuel in an engine exhaust could prove to be a significant problem. Any future work on safety fuels should define ignition and burning characteristics more precisely and should minimize the possibility of ignition of entrained fuel. Any new work in this area should also consider new and improved antimisting additives as well as alternate approaches (reference 66). FAA has concluded that the CID was an experimental failure, not a failure of the antimisting fuel.

Additional consideration should also be given to some technical problems uncovered in pre-CID research. For example, a more complete explanation is required for the insoluble gel that occurred in FM-9 AMK during some early flight and engine test cell work. An adequate answer is also required for the granular gel that forms when normal kerosene fuel is added to a system containing residual AMK and exposed to high shear rates (reference 32). The significance of this problem to commercial operation must be more fully evaluated in any future program.

Future safety fuels, when combined with a systems approach, should prove to be effective in reducing post-crash fire hazards in commercial air transportation and merit the continued attention of air safety researchers.

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APPENDIX A

MEMORANDUM OF UNDERSTANDING

FAA/AIS/CA-11

MEMORANDUM OF UNDERSTANDING

between

THE GOVERNMENT OF

THE UNITED KINGDOM OF GREAT BRITAIN
AND NORTHERN IRELAND

represented by

THE UNITED KINGDOM PROCUREMENT EXECUTIVE OF
THE MINISTRY OF DEFENCE

and

THE GOVERNMENT OF THE UNITED STATES OF AMERICA

represented by

THE UNITED STATES
DEPARTMENT OF TRANSPORTATION/FEDERAL AVIATION
ADMINISTRATION

concerning

CO-OPERATION IN THE TESTING AND DEVELOPMENT

of

ANTI-MISTING KEROSENE AND RELATED EQUIPEMENT

SHORT TITLE

AMK

SECTION I

INTRODUCTION

A. The Government of the United Kingdom of Great Britain and Northern Ireland, represented by the Procurement Executive of the Ministry of Defence (MOD (PE)) and the Government of the Unites States of America represented by the Department of Transportation, Federal Aviation Administration (DOT/FAA) with the purpose of saving lives and property through reducing the number and severity of fires following aircraft accidents in which there are survivors of the impact, intend to co-operate in the examination, development and testing of anti-misting kerosene fuels and of equipment related to the use of such fuels.

B. This co-operation will be undertaken by the MOD (PE) and the DOT/FAA each pursuing with their associates and contractors a part of the program of work set out in the Appendix to this Memorandum of Understanding.

C. This Memorandum of Understanding sets out the arrangements and procedures established by the Governments for co-operation in the carrying out of the program of work.

SECTION II

DEFINITIONS

In this Memorandum of Understanding:

(1) "Government" means the MOD (PE) or the DOT/FAA as the context may require; and "Governments" mean the MOD (PE) and DOT/FAA.

(2) "Program of Work" means the work set out in the Appendix to this Memorandum of Understanding.

(3) "Related Work" means work relating to anti-misting safety fuels for use in aircraft carried out before the day of entry into operation of this Memorandum of Understanding by the representatives or agencies or by an agent or contractor of either of the Governments or by a body under the control of either of the Governments.

(4) "Facility" means a laboratory test location or research establishment under the control of or under contract to one of the Governments.

SECTION III

MANAGEMENT

A. Each Government will appoint initially three members to a Management Group, whose function will be to undertake on behalf of the Governments the review of policy relative to, and general direction of, the program of work. Meetings of this Management Group will be held alternately in the United States and in

the United Kingdom, and will be convened by a chairman, chosen from the members appointed by the host country. In the case of the United States, the co-chairman, and one other, will be from the DOT/FAA and the third will be from the National Aeronautics and Space Administration. In the case of the United Kingdom, the co-chairman will be from the MOD (PE) and the one representative each from the Department of Industry and the Civil Aviation Authority.

B. The Management Group will meet, as required, to review progress and establish program guidance and priorities at significant decision points in the program. It is expected that this will normally be not more than twice and not less than once a year. It is hoped in particular that a decision can be taken by the Management Group as early as possible, within the first two years of operation of the Memorandum of Understanding, as to the overall viability of this program of work. Such a decision will take into account the technical issues, the potential cost, and the prospects for international implementation of anti-misting kerosene fuels.

C. The Management Group will approve the appointment of two Project Officers, one from the DOT/FAA and one from the MOD (PE). These Project Officers will act alternately as chairman of a joint Technical Group to be responsible for the technical supervision of the program. Each Project Officer will select, with the approval of the appropriate National Co-Chairman of the Management Group, a maximum of four members each from the United States and the United Kingdom respectively for the Technical Group. In addition, as necessary, the two Project Officers may invite additional representation from specialized areas of technical expertise and experience.

D. Each Project Officer, advised by the Technical Group, will be responsible to the Mangement Group for:

(a) The implementation of his own Government's respective part of the program of work.

(b) The co-ordination of, and any modification of, the parts of the program of work. Modifications to the program will be effective provided that they are set out in writing, signed by both Project Officers, and endorsed by the Management Group.

(c) Exchange of information arising from the program of work and related work in accordance with Section VI of this Memorandum of Understanding.

Meetings of the Technical Group will normally be held alternately in the United States and the United Kingdom, and will be arranged by the Project Officers as the work program requires.

The Project Officers will report, as required, to their respective Management Group Chairmen and may be invited to be in attendance at the meetings of the Management Group.

SECTION IV

COSTS AND SUPPLY OF MATERIALS

A. The cost of performing any item of the program of work will be borne by the Government in whose facility the item of work is performed unless otherwise specifically agreed by the Management Group.

B. The supply of information, material, or equipment by one Government to the other for the purpose of carrying out the program of work will normally be at the cost of the recipient Government but the cost chargeable to the recipient Government will be limited to the actual cost of procurement by the supplying government plus normal transportation, insurance costs, and identifiable taxes and customs duties. These arrangements may be varied in specific instances by the Management Group.

C. Either Government may loan to the other information, equipment or material.

D. The recipient Government will use the information, material or equipment only for the purpose of the program of work and in cases of loans, will return the information, material, or equipment at the request of the supplying Government and in accordance with the applicable law.

E. Any arrangement necessitating transfer of funds, arising out of the transfer or loan of information, material, or equipment from one country to the other will be the subject of a separate arrangement between the Government or their respective agencies.

SECTION V

ACCESS TO FACILITIES

A. Each Government will afford all the members of the Technical Group appointed by the other Government (and any person acting for the other Government and authorized by the two Project Officers) access to its facilities for the purpose of aiding appreciation of the performance of any item of the program of work which may be in progress at the facility.

B. This access will be subject to reasonable notification and to the normal security restrictions in existence at the facility and will be subject to the provisions of Section VI and VII of this Memorandum of Understanding.

SECTION VI

EXCHANGE, USE AND COMMERCIAL SECURITY OF INFORMATION

A. The Governments intend, subject to the rights of third parties, to exhange regularly information in their possession and which relates to their respective part of the program work. The information will be exchanged only through the medium of or with the concurrence of the Project Officers. All

information exchanged will be, so far as is practical, in the form of documents.

B. The exchange of information will be on the basis that the information is supplied only for study and evaluation by the recipient Government and that the information will not, without the prior approval in writing of the Government supplying the information, or the owner of the information, be passed to a third person except as may be required by applicable law or published or used for the design, development, or improvement of equipments, chemical products or processes.

C. In furtherance of paragraph B above, each Government will make every effort that it legally may to maintain the information free from any liability to disclosure under any present or future legislative provisions. Each Government may mark documents transmitted to the other with words indicating their owner, their country of origin, that they relate to the program or work, and that they are furnished under conditions of confidence (i.e., are not to be disclosed to or used by a third party without the prior permission of the transmitting Government) or alternatively establishing the conditions of release. The recipient Government will confirm that the documents are received under the conditions indicated.

D. At the specific request of the transmitting Project Officer setting forth the reasons for the request, the intended recipient Project Officer will review documents prior to formal receipt and advise the other Project Officer of his Government's view of its ability to maintain the confidentiality of the documents under applicable law. In doubtful cases, the Project Officers will, consult concerning what steps can be taken to provide for confidentiality. It is the understanding of the Governments that this provision should be invoked only in the most unusual circumstances.

E. Each Project Officer will ensure that any request under applicable law for disclosures of information in documents originating in the other country and furnished in accordance with this Memorandum of Understanding is promptly notified to the other Project Officer to afford the latter the opportunity to object to disclosure. The notification will identify applicable time limits and the legal principles involved in the request. If the Government processing the request determines that the requested information cannot legally be withheld, the Government's Project Officer will so advise the other Project Officer sufficiently in advance of the projected disclosure date to permit the latter to initiate whatever steps are deemed appropriate. In cases involving loaned information, the information will be returned to the lender, in accordance with the applicable law.

F. Each Government will grant to the other, or to a person nominated by the other, a licence on fair and reasonable terms to use, for commercial purposes in the United Kingdom and the United States and in other countries to which the licence may be extended under relevant laws and regulations, patented inventions and confidential technical information owned by the Government granting the licence and arising out of its respective part of the

program of work. Each Government will also grant a similar licence in respect of patented inventions and confidential technical information which it owns and which arose out of related work.

G. In the event that personnel of both Governments or their contractors participating in the program of work make a joint invention, design, or discovery, then both Governments will in accordance with their national laws take appropriate action to ensure that both Governments or persons nominated by either of them will have the right to the free use for commercial purposes, in the United Kingdom and the United States and in other countries to which the licence may be extended under relevant laws and regulations, of the joint invention, design, or discovery. The appropriate action may include making joint application for a patent and the assigning of the patent to one or jointly to both Governments and the granting of a free licence to one or both Governments or to a person nominated by either Government.

H. Any such licence as is referred to in paragraphs F or G of this Section will include the provision that the licencee will be obliged to inform the licencor of all developments, improvements, or inventions that the licencee may make in relation to the subject of the licence and will be obliged to grant a return licence on fair and reasonable terms to the licencor in respect of all the developments, improvements or inventions so made should the licencor so wish.

I. Each Government will use its good offices to arrange for a licence as described in paragraph F of this Section to be granted by a third person who may own relevant patented inventions, designs, discoveries or confidential information in respect of which Government does not have the right to grant such licences.

SECTION VII

MILITARY SECURITY

A. All classified information or material or equipment supplied in accordance with Section IV and VI will be protected in accordance with established security arrangements between the Government of the United Kingdom and the Government of the United States of America.

SECTION VIII

LIABILITY

Neither Government will be liable to the other for any damage, loss, or injury to personnel, material, or equipment occasioned by or during any activities undertaken pursuant to this Memorandum of Understanding.

SECTION IX

INTERPRETATION, APPLICATION AND MODIFICATION

Any disagreement regarding the interpretation or application of this Memorandum of Understanding will be resolved by consultation between the Governments and will not be referred to any international tribunal or third party for settlement.

The terms of this Memorandum of Understanding may be modified as provided in Section IIID or by the Governments. In the second case, any modification will enter into operation on signature by the duly authorized representatives of the Governments.

SECTION X

ENTRY INTO OPERATION AND TERMINATION

A. This Memorandum of Understanding will enter into operation on the date on which it is signed on behalf of the two Governments. The program of work will be pursued for at least two years from the date on which this Memorandum of Understanding enters into operation. Either Government may terminate the pursuit of its respective part of the program of work after giving 90 days notice in writing.

B. In the event that one or both Government terminate their participation in the program of work the understandings concerning exchange, use and commercial security of information as set out in Section VI and concerning Military Security as set out in Section VII will remain in effect.

SECTION XI

SIGNATURES OF AUTHORIZED REPRESENTATIVES

A. The foregoing represents the understandings reached between the Government of the United Kingdom of Great Britain and Northern Ireland represented by the Procurement Executive of the Ministry of Defence and the Government of the United States of America represented by the Department of Transportation, Federal Aviation Administration upon the matters referred to therein.

UNITED STATES represented by DOT/FEDERAL AVIATION ADMINISTRATION	UNITED KINGDOM represented by MINISTRY OF DEFENCE PROCUREMENT EXECUTIVE
By: Norman H Plummer	By: [illegible signature]
Title: Assistant Administrator for International Aviation Affairs (Acting)	Title: Director of [illegible]
Date: June 1, 1978	Date: 14 June '78

. Appendix see over

APPENDIX B

DISTRIBUTION LIST

APPENDIX B

STANDARD DISTRIBUTION LIST

Region Libraries

Alaska	AAL-64
Central	ACE-66
Eastern	AEA-62
Great Lakes	AGL-60
New England	ANE-40
Northwest-Mountain	ANM-60
Western-Pacific	AWP-60
Southern	ASO-63d
Southwest	ASW-40

Center Libraries

Technical Center	ACT-64
Aeronautical Center	AAC-44.4

Civil Aviation Authority
Aviation House
129 Kingsway
London WC2B 6NN England

Embassy of Australia
Civil Air Attache
1601 Mass Ave. NW
Washington, D. C. 20036

Scientific & Tech. Info FAC
Attn: NASA Rep.
P.O. Box 8757 BWI Aprt
Baltimore, Md. 21240

DOT-FAA AEU-500
American Embassy
APO New York, N. Y. 09667

Headquarters (Wash. DC)

ADL-1
ADL-32 (North)
APM-1
APM-13 (Nigro)
ALG-300
APA-300
API-19
AAT-1
AWS-1
AES-3

OST Headquarters Library

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Sers Dpt Inst of Trsp Std Lib
412 McLaughlin Hall
Berkely, CA 94720

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Civil Air Attache ATS
3100 Mass Ave. NW
Washington, DC 20008

Dir. DuCentre Exp DE LA
Navigation Aerineene
941 Orly, France

Northwestern University
Trisnet Repository
Transportation Center Lib.
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